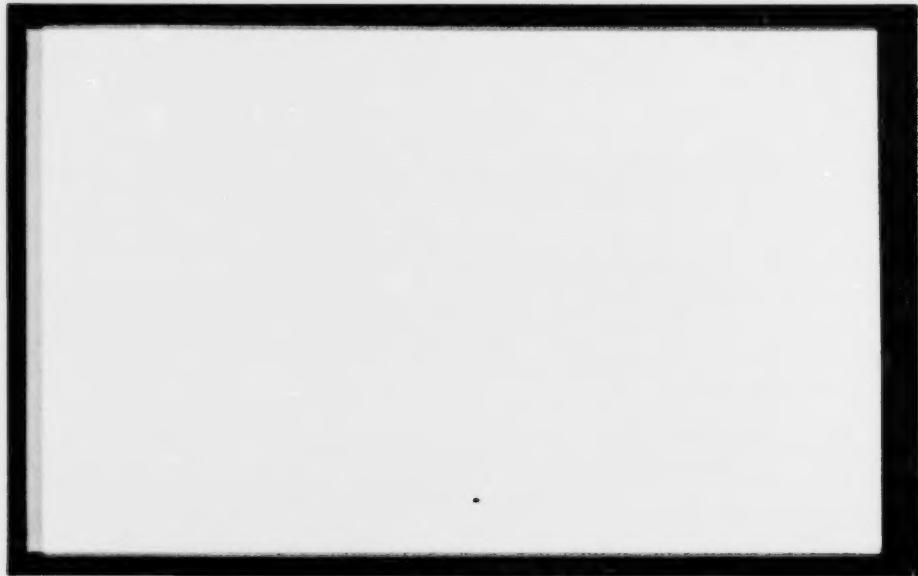


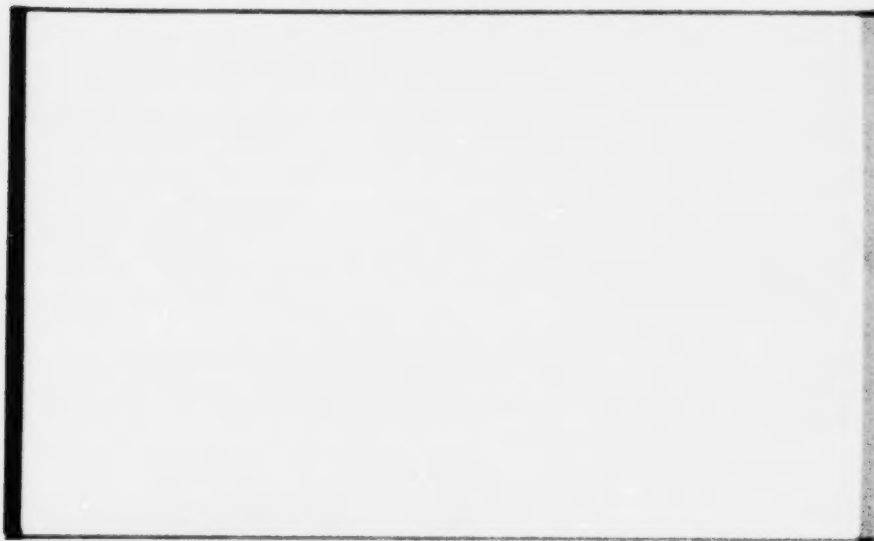


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HEAVY OIL PROJECT



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POTENTIAL ENVIRONMENTAL EFFECTS OF DRILLING WASTES ON
CROPS AND SOILS IN SASKATCHEWAN,
PHASE I: PRELIMINARY EVALUATION
VOLUME I

by
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EXECUTIVE SUMMARY

Introduction

The main objective of this study is to provide an overview of the potential impact of drilling waste disposal on soils, crops and natural vegetation in the oil and gas producing regions of Saskatchewan. The study was based on a review and assessment of available literature, drilling waste chemistry data and drilling mud formulation information.

Major Findings and Conclusions

General

(1) Large volumes of waste (approximately 12.7 million barrels) are being generated annually as a result of drilling for gas and oil in Saskatchewan.

(2) Land application of drilling wastes can affect seed germination; plant growth, yield and cover; and soil physical and chemical properties. However, the magnitude and direction (negative or positive) of the impact would vary with such factors as waste characteristics and application rate, and the properties of the receiving environment.

Environmental Interactions

(3) The relative detrimental effects of the main drilling fluid systems can be ranked, in order of decreasing detrimental effects, as follows:

- * salt base systems
- * diesel oil systems, and
- * freshwater systems

(4) The vast majority of the drilling fluid systems, particularly those disposed of by land spreading, are of the freshwater type, which is least detrimental to plants and soils. However, a great deal of variability in chemical characteristics is evident among the different freshwater sump fluids.

(5) A one-time application of freshwater drilling wastes to agricultural land and naturally vegetated sites at the rate recommended by the Saskatchewan Energy and Mines (100 bbls/acre) is unlikely to result in significant reduction in plant growth or yield, or significant changes in soil properties.

(6) Present on-site disposal rates and practices could, in many cases, result in significant reduction in plant cover, growth and yield and in significant alteration of soil chemical and physical properties. The effects could be of temporary or long-term nature, depending on waste and site characteristics and site closure measures.

(7) Under certain conditions (e.g. coarse-textured, acidic soils), low application rates of freshwater/gel drilling wastes may be beneficial to plants and soils. The apparent beneficial effects associated with some cases of land application of freshwater systems may be related to:

- * increased soil water holding capacity,
- * improved soil structure,
- * raised pH, and
- * improved soil nutrient status.

(8) The main drilling waste parameters of concern appear to be:

- * salinity and specific ion content,
- * sodicity,

- * trace element content,
- * unidentified factors (organic toxicity?)

(9) Under field conditions, salinity and/or sodicity account for most of the detrimental effects.

(10) Present on-site application rates of drilling wastes could result in elevated levels of certain trace elements (mainly B, Cr, Mo, Mn and Zn) in the soil. The significance of this change, in terms of plant toxicity, may be somewhat masked by:

- * the binding ability of the soil,
- * the dominant influence of salinity and sodicity, and
- * the possible beneficial effects of other components.

(11) Some of the heavy metals introduced into the soil as a result of waste application are available for uptake by plants. The potential for significant food chain transfer is, however, low because only a small portion of the added metals are actually taken up by plants.

(12) In some cases, activities associated with drilling site construction and operation (e.g. topsoil disturbance, compaction) could result in greater damage to the soil than land application of the waste.

Mitigation

(13) The detrimental effects of land spreading of drilling wastes can be eliminated or reduced through such predisposal measures as:

- * selection of nontoxic drilling fluid additives,
- * reduction in volume of waste generated by means of recycling and reuse,
- * sump fluid treatment,

- * good housekeeping practices, and
- * consideration of alternate disposal methods (e.g. deep-well injection, approved disposal sites).

(14) Soil damage resulting from salinity can be reclaimed, through leaching, by natural or artificial means in a relatively short time (several months to few years), depending on the severity of the problem, soil characteristics, site drainage and climatic conditions, particularly precipitation.

(15) Soil damage resulting from high sodium content of the waste can be mitigated through the use of appropriate amendments and leaching.

(16) Soil damage resulting from oil may be mitigated, at least in the topsoil, through tillage and proper fertilization.

Recommendations

(1) Firms engaged in drilling operations in the province should be encouraged to:

- * select the nontoxic or less toxic drilling fluid additives and drilling fluid systems,
- * reuse drilling fluids, particularly those identified to be detrimental to plants and soils,
- * plan site layout and pit design that will ensure proper containment of the waste, and
- * enforce appropriate housekeeping rules with emphasis on such aspects as minimizing volume of waste generated, chemical spills and site disturbances.

(2) Agricultural land spreading, both on-site and off-site, of salt

based drilling sump fluids and oil based sump fluids should be avoided. Firms using or planning the use of these fluid systems should employ other acceptable disposal options (e.g. subsurface disposal through deep-well injection, use of approved waste disposal facilities).

(3) Off-lease disposal of freshwater sump fluids could be continued with no significant impact anticipated, provided that the maximum application rates and quality criteria indicated in the Approval Guidelines developed by the Saskatchewan Energy and Mines are enforced.

(4) On-lease disposal guidelines should be developed. Although appropriate field data necessary for the formulation of such guidelines are lacking at present, the report provided interim criteria, based on experience gained in other jurisdictions, for consideration by the Department of Energy and Mines.

(5) Site reclamation guidelines should be developed. It is recommended that the objective of reclamation should be to restore the productivity to a level equal to or greater than the original conditions.

(6) It is recommended that a list of recognized analytical laboratories, where sump fluids and soils may be analyzed, be prepared. Active participation in the Canadian Quality Assurance Program should be the minimum qualification requirement.

(7) It is recommended that further studies be carried out to test the conclusions reached in this study under the Saskatchewan conditions in order to provide quantitative data necessary for the formulation of environmental protection guidelines and to investigate the long-term effects of drilling waste disposal on agricultural land.

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1 INTRODUCTION

1.1 General

Saskatchewan is the second largest producer of crude oil in Canada. The value of oil shipments reached more than \$1.6 billion in 1983, representing 60% of total provincial mineral shipments. In 1984, more than 2500 exploration and production wells were drilled in the four oil producing regions of the province, i.e. Lloydminster, Kindersley, Swift Current and Estevan (Figure 1.1). These activities have resulted in a provincial government revenue of \$700 million in the form of taxes, sales of oil and gas rights, and royalties. This level of activities will likely be maintained or increased in the coming years due to such factors as tax incentives (e.g. the Oil Industry Recovery Program), crude oil price deregulation, new enhanced oil recovery techniques and possible increase in future energy demand.

As part of its commitment to environmental protection, the Saskatchewan Government, through the Department of Energy and Mines, has initiated or funded a number of studies, including the present study, to investigate the environmental implications and possible mitigation measures of the increased oil development activities (Walker 1985). This study addresses the potential environmental problems associated with the disposal of the wastes generated from the oil and gas drilling operations.

1.2 Objectives and Methods

The main objective of this study is to provide an overview of the potential impact of drilling waste disposal on soils, crops and natural vegetation in the oil producing regions of Saskatchewan. The study terms

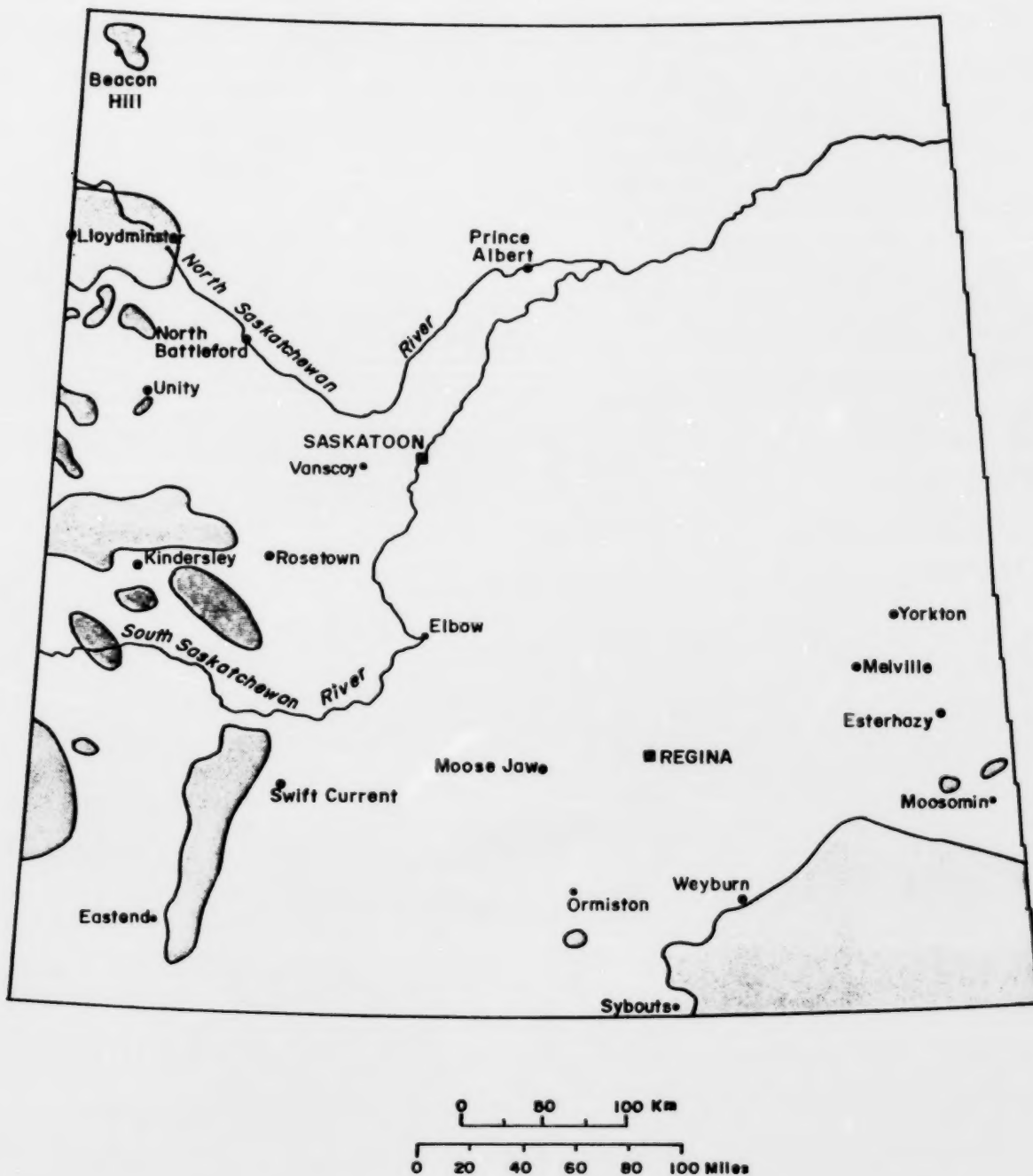


Figure 1.1 Oil and Gas Producing Areas (Shaded) in Saskatchewan.

of reference are given in Appendix A.1.

Drilling waste, as used in this report, refers to sump or reserve pit contents. These include spent drilling fluids (muds), cuttings (drilled solids), and other waste material generated during the drilling operations. Upon completion of drilling, much of the drilling waste is surface deposited on the lease and the surrounding areas.

The study approach, as illustrated in Figure 1.2, consisted of:

- * determining the characteristics of the waste generated and the potential receiving environment; and
- * evaluating the potential waste-receiving environment interactions taking into consideration the knowledge acquired concerning the nature of the waste and the receiving environment and the pertinent literature.

The approach used recognized the modifying influence of climatic conditions, prevailing agricultural practices and the present environmental disposal and mitigation measures.

Two different methods were employed to characterize the drilling waste. A questionnaire (Appendix A.2) was sent to all Saskatchewan firms engaged in activities related to drilling for oil and gas as listed in the 1984/1985 telephone directories¹. The questionnaire was designed to obtain information on:

- * types of drilling fluid systems used in the various regions of the province,
- * the formulation (composition) of the different fluid systems identified, and
- * the present drilling waste disposal methods.

¹In some cases, the head office in Calgary had to be contacted.

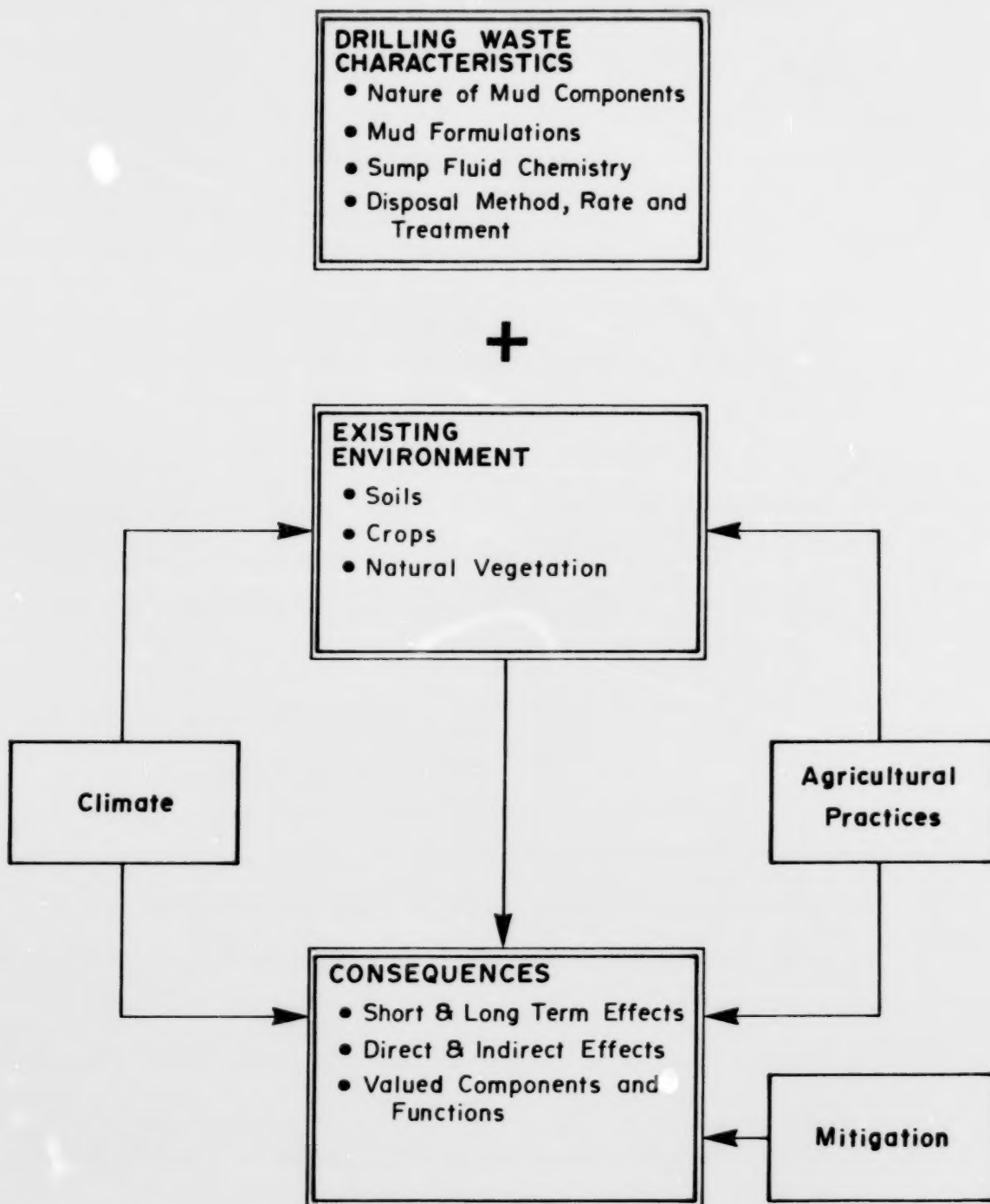


Figure 1.2 The Approach Used to Analyze the Potential Waste-Environment Interactions.

A list of the firms which responded to the questionnaire, up to June 7, 1985, is given in Appendix A.3.

In addition, available sump fluid chemistry data, obtained through the Petroleum Development Branch of the Saskatchewan Department of Energy and Mines, were synthesized and evaluated. Most of these data came from the Lloydminster and Kindersley regions. The parameters consisted of detailed salinity analysis and trace element determination. No organic or radionuclide analyses were available.

Regional characterization of the receiving environment was based on existing information.

An on-line computer data base search of the following files was carried out:

- * ENVIROLINE,
- * Pollution Abstracts,
- * Environmental Bibliography,
- * CA Search, and
- * NTIS (U.S. National Technical Information Services).

The literature review was augmented by an examination of relevant material presented at recent conferences and workshops on the subject of drilling waste disposal.

Numerous personal contacts (Appendix A.4) were made with researchers, government officials, oil industry personnel and others to secure additional information pertaining to the study.

No fieldwork was conducted in conjunction with this study. However, air photo interpretation was performed to provide a general and preliminary evaluation of selected sites.

2 EXISTING ENVIRONMENT

2.1 Regional Considerations

A summary of the regional environmental information is given in Tables 2.1 to 2.3.

The climate of the oil producing regions of the province is classified semiarid to dry subhumid with mean annual precipitation ranging from 305 to 406 mm.

Black Chernozemic and Dark Grey soils are dominant in the less arid areas (i.e. Lloydminster), while Brown and Dark Brown Chernozemic soils are prevailing in the other regions. Soil organic matter ranges from approximately 3% in the Brown soils to nearly 6% in the Dark Grey soils (Rennie and Ellis 1978). The Dark Brown and Black soils are characterized by intermediate levels of organic matter. The Estevan and Swift Current regions are characterized by higher pH and greater salinity risk than the other two regions.

The potential natural vegetation is a mixed prairie grassland type in all regions with the exception of the Lloydminster area. In the latter area, the natural vegetation consists of a mosaic of open woodland and grassland types. However, most of the natural vegetation cover in these regions has been removed for crop production. Most of the remaining natural vegetation is found in areas that are unsuitable for cultivation.

Field crop production is the main type of land use in the four regions. Wheat is the most important crop in the Kindersley, Swift Current and Estevan regions. Wheat, barley and canola are the main crops in the Lloydminster area. No data were found on the areal extent of land under

Table 2.1 Climate and Potential Natural Vegetation in the Oil Producing Regions of Saskatchewan*.

Parameter	Regions		
	Lloydminster	Kindersley	Swift Current
<u>Climate</u>			
Climatic classification	Dry subhumid	Semi-arid	Semi-arid-Dry sub-humid
Annual precipitation (mm)	359**	305-356	406
Mean number of degree days above 5°C	1210	1320	1540
<u>Vegetation</u>			
Ecological district	Aspen grove	Mixed prairie	Mixed prairie
Dominant vegetation	Aspen/bluegrass-sarsaparilla	Spear grass - wheatgrass, wheatgrass - June grass	Spear grass - wheatgrass, spear grass - blue grama

* Source: see Appendix B.1.

** Based on 30-year normal for North Battleford. No precipitation data are available for Lloydminster but it is expected to be somewhat higher than that for North Battleford.

Table 2.2 Selected Soil Characteristics in the Four Oil Producing Regions of Saskatchewan*.

Soil "Parameters"	Regions			
	Lloydminster	Kindersley	Swift Current	Estevan
Soil zone	Black	Brown-dark brown	Brown	Dark brown
Cation exchange capacity	Moderate to high	High	Moderate to high	High
Texture	Coarse to fine	Medium to fine	Coarse to medium	Medium to fine
Dominant pH	<6.5	5.5 - 7.5	>6.5	>6.5
Dominant salinity risk class	Moderate	Moderate	High	High
Dominant salt	Magnesium and sodium sulfate	Sodium sulfate	Sodium sulfate	Sodium sulfate (Some high in chlorides)

* Source: see Appendix B.1.

Table 2.3 Cropping Pattern (as % of cropped land) in the Oil Producing Regions of the Province*.

Crops	Regions			
	Lloydminster	Kindersley	Swift Current	Estevan
Wheat	46	77	91	84
Barley	25	15	5	9
Oats	8	3	3	4
Canola	20	3	0	0
Flax seed	1	2	<1	3

*Saskatchewan Agricultural Statistics, Saskatchewan Department of Agriculture, Regina (1982).

cultivated hay and improved pasture. Land areas supporting natural vegetation are used for livestock and wildlife grazing.

In recent years, dryland salinity has become a major agricultural problem in many areas in Saskatchewan. Rennie and Ellis (1978) indicated an increase in the salt affected area in the province from 400,000 ha in 1960 to 1,620,000 ha in 1977. The increase in dryland salinity is likely related to a combination of cultural, climatic and hydrogeological factors.

A considerable decline in soil organic matter and fertility levels (particularly nitrogen) and deterioration in soil structure has been noted for much of the agricultural areas in the province.

Some degree of soil erosion is expected even under undisturbed natural conditions. However, the present agricultural practices appear to have accelerated the rate of soil losses by wind and water. Johnson (1961) estimated that 2.1 million ha in Saskatchewan and Manitoba were significantly affected by erosion.

The natural vegetation is influenced greatly by climatic conditions as well as by grazing practices. Substantial changes in plant species composition can result from a series of dry years. Similar changes often result from overgrazing by domestic animals.

2.2 The Soil-Plant System

In this section, some of the important properties of the soil-plant system are described. Emphasis will be on those parameters of importance in predicting the potential soil-waste interactions.

The soil can be viewed as a three-phase system with solid, liquid,

and gaseous components, each of which has its own physical and chemical properties but all are interrelated with each other. In addition to these components, each soil has a distinctive assemblage of soil organisms (e.g. bacteria, fungi, algae) performing many important functions.

The solid phase is represented by inorganic (mineral) and organic matter. The mineral portion consists of particles of rocks and minerals varying in size from gravel and sand to clay. Clay particles carry a negative charge which enables them to attract positively charged ions to their surfaces. In Saskatchewan soils, montmorillonite has been found to be the predominant clay mineral with illite usually a major constituent (Rennie and Ellis 1978).

The relative proportions of particles of various size classes are used to classify the soils into textural classes. Texture has a profound influence on the soil-plant relationships, particularly through its effects on important parameters such as water holding capacity, cation exchange capacity and soil structure.

Organic matter is the product of decomposition of plant and animal residues by soil organisms and is present in various degrees of decay and stability. The negative charges on the organic matter particles are responsible for its high cation exchange capacity. Organic matter affects the physical properties of soils, particularly structure, water holding capacity and aeration. It also acts as a source of important plant nutrients and as a source of energy for soil organisms.

The gaseous (soil air) and liquid (soil water) phases occupy the porespace between the solid soil particles. The amount of porespace available varies with soil texture, structure and organic matter content.

For optimum plant growth both soil air and soil water must be present in the right proportions. A soil with excess water is unfavourable for normal plant growth. On the other hand, a soil containing much air and little water is in a "droughty" state. The soil air/water status also affects the type and level of soil microbial activities.

Soil microorganisms perform many important functions. Of particular significance to higher plants is the decomposition of organic residues. This process results in the release of nutrients held in organic combination with these residues, which is acted upon by other organisms to produce forms that are available for uptake by plants. Fixation of free nitrogen from the air is another important function of certain organisms such as the bacteria associated with the roots of legumes.

3 DRILLING WASTE CHARACTERISTICS

3.1 General

Drilling waste, or sump contents, are made up of:

- * drilling fluids,
- * drilled solids (formation cuttings),
- * rig wash, fuels and lubricating oils from the rig operation, and
- * other wastes (e.g. sewage)

The amount of waste generated from a well drilling operation depends to a great extent on the drilling depth, problems encountered and number of fluid system changeovers. The average depth varies within and between regions and is estimated to be 620, 760, 800 and 1350 m for the Lloydminster, Kindersley, Swift Current and Estevan regions, respectively. According to the latest Drilling Activity Report, some of the wells in the Estevan area are drilled to a depth of 2000-3000 m.

On the basis of the present drilling waste disposal practices, it is estimated that in 1984 alone 22,500 ha (55,600 acres) of agricultural land were needed to dispose of these wastes (Appendix C.1). A relatively small area was required in the Estevan and Swift Current regions because disposal is largely restricted to the lease area. By 1990, a total of 130,000 ha (320,000 acres) would be involved in drilling waste disposal.

Projected waste volumes and land area required for disposal are given by region for the years 1985-1990 in Appendix C.1.

A typical mud system is illustrated in Figure 3.1. The mud route during a closed-circuit drilling operation is indicated by arrows. Of importance to the purpose of this study is the type of materials released into the sump. These include:

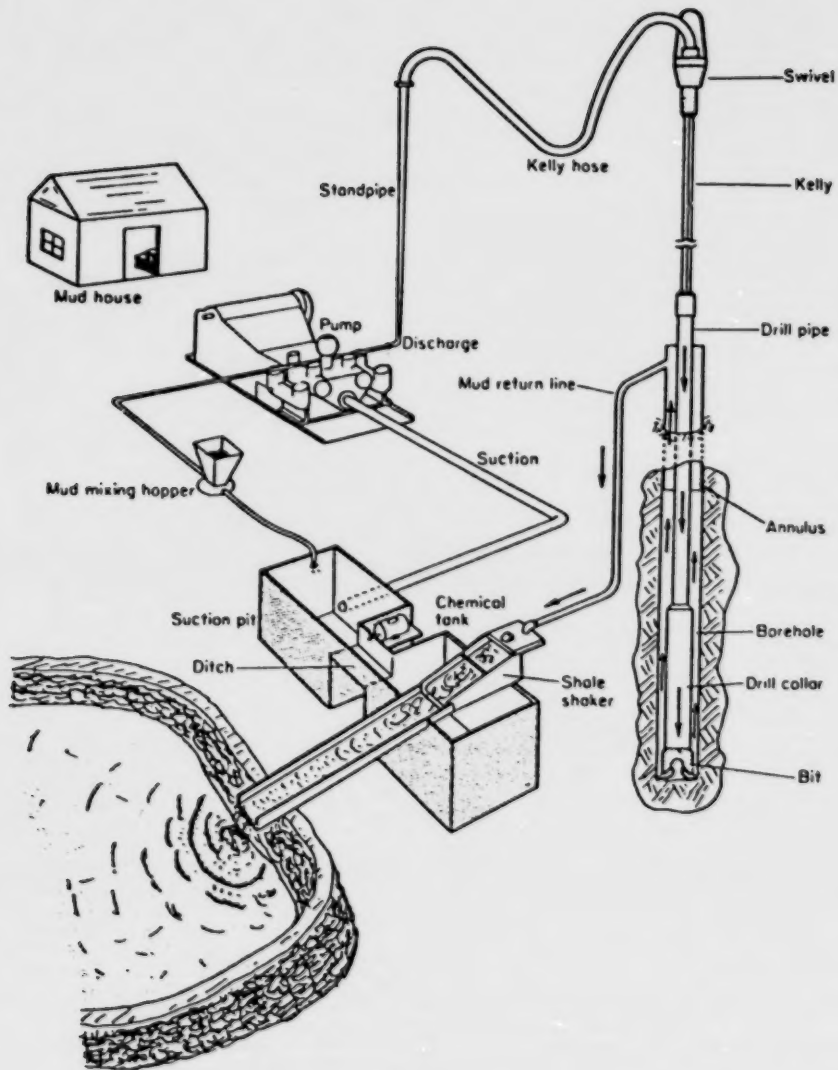


Figure 3.1 A Typical Mud System.

- * the spent fluids and cuttings resulting from the drilling of the surface hole,

- * the formation cuttings, usually coated with drilling fluids, from the shale shaker during the drilling of the main hole,

- * drilling fluids that have become unsuitable because of change in downhole conditions or problems with solid control equipment,

- * spent drilling fluids from the main hole after the total depth is reached, and

- * other wastes as indicated earlier in this section.

3.2 Drilling Fluid Systems and Components

The primary functions of drilling fluids include:

- * transport drill cuttings to the surface,

- * control formation pressure,

- * maintain borehole stability,

- * protect productive formations,

- * protect against corrosion of pipes, casings, etc., and

- * cool and lubricate the bit and drill string.

To perform these functions, specific physical and chemical properties must be achieved by use of a variety of additives. Mosely (1983) estimated that more than 700 mud additives are currently available in the market. However, usually less than ten additives are used in a single drilling operation. In Saskatchewan, at least 45 additives are commonly used. A list of these additives and their functions is included in Appendix C.2.

Drilling fluids used in Saskatchewan may be grouped into three broad

categories:

- * freshwater base muds,
- * salt water base muds, and
- * oil base muds.

The vast majority of the drilling fluids used in Saskatchewan are freshwater systems (Table 3.1). Of these, the freshwater/gel (bentonite) is the most commonly used in all regions. The freshwater/polymer systems are used more in the Lloydminster and Kindersley areas than in the other two regions. Other less common water systems include potassium chloride (KCl)-polymer, sodium chloride (NaCl), NaCl-polymer and potassium sulfate (K_2SO_4)-polymer.

Oil base systems were restricted to the Kindersley region and represented less than 1% of the total number of wells surveyed.

The selection of the type of fluid system depends on many factors including:

- * predicted and actual conditions encountered during drilling (e.g. formation pressures, formation permeability, presence of salt formation, presence of sensitive shale formation, depth),
- * availability and cost of the system, and
- * preferences of the supplier and the operator.

The first factor, however, is given the greatest consideration in selecting a system.

The detailed drilling fluid formulation information is given in Appendix C.3. The frequency of use of the various components of the freshwater/gel system are given in Table 3.2. The most frequently (>50% of the cases) used components are bentonite, soda ash (sodium carbonate),

Table 3.1 Frequency of Utilization of the Various Drilling Fluid Systems in the Oil Regions of Saskatchewan.

	Frequency (%)*			
	Lloydminster	Kindersley	Swift Current	Estevan
FRESHWATER SYSTEMS				
- Gel/water	75	83	90	80
- Polymer/water	13	16	0	4
- CaCO ₃ weighted	2	0	10	13
SALT WATER SYSTEMS				
- NaCl	1	--	--	2
- NaCl/Polymer**				
- KCl/Polymer	9	--	--	--
- K ₂ SO ₄ /Polymer**				
OIL BASE SYSTEMS		<1		

* Frequency is based on a survey of 411 wells.

** These systems were not identified in the above-mentioned survey. Their use was indicated in information supplied by SEM.

Table 3.2 Frequency of Use and Maximum Projected Soil Concentrations of the Various Components of the Freshwater/Gel Drilling Fluid Systems.

Component	Frequency (%)	Projected Concentration in Soil (g/kg)**
Attapulgate	3	0.2
Barite	12	0.5
Bentonite	100	1.46
Calcium chloride	<24*	0.38
Calcium hydroxide	59	0.03
Detergent	3	0.1
Diesel oil	<24*	0.3
Gelex	3	0.01
Iron chromelignosulfonate	34	0.15
Lignite	44	0.03
Modified lignosulfonate	6	0.01
Paraformaldehyde	3	0.02
Polysaccharides	<24*	0.05
Plant and synthetic fiber mix	<24*	0.01
Polyacrylamide polymer	34	0.1
Polyacrylic polymer	<10*	0.05
Polyanionic cellulose	9	0.03
Sawdust	56	0.2
Sodium bicarbonate	25	0.05
Sodium acid pyrophosphate	41	0.02
Sodium carbonate	91	0.18
Sodium carboxymethyl cellulose	31	0.05
Sodium hydroxide	81	0.08
Sodium polyacrylate	6	0.02
Starch	3	0.39
Xanthan gum	<10*	0.01

* Could not calculate exact frequency, due to insufficient data

** Based on an off-lease disposal rate of 247 barrels/ha and a hectare furrow slice of 2.2×10^6 kg.

caustic soda (sodium hydroxide), lime (calcium hydroxide) and sawdust.

In order to facilitate the discussions on the possible effects, the various drilling fluids may be classified on the basis of their chemistry into the following classes:

- * organic constituents - these include (1) additives of petroleum origin such as diesel oil and crude oil, (2) lignite and sulfonates, (3) polymers and (4) other materials of plant origin such as starches, plant fibers and sodium carboxymethyl cellulose (CMC); and

- * inorganic constituents - including (1) soluble salts such as KCl, NaCl, caustic soda (NaOH) and sodium acid pyrophosphate (SAPP), and (2) inert or nearly insoluble materials such as bentonite and barite (barium sulfate).

Drilling fluid components containing trace elements include iron chromelignosulfonate, crude oil, heavy metals salts added to prevent microbial degradation, and impurities in such additives as barite. Nelson (1984) indicated that synthesized drilling fluid systems contain varying levels of barium (Ba), cadmium (Cd), zinc (Zn), copper (Cu), chromium (Cr), lead (Pb), mercury (Hg) and arsenic (As).

3.3 Sump Fluids

As indicated in Section 3.1, reserve pits contain wastes from various sources in addition to the spent drilling fluids. It is, therefore, important to examine the nature and chemistry of sump fluids. In general, pit contents consist of three distinct phases:

- * a thin layer of oil scum on the surface,
- * a large aqueous (liquid) phase with dissolved components and sus-

pended solids, and

* a bottom layer of sludge containing most of the solids which have settled (Specken 1975).

Sump fluids, particularly those containing a high concentration of suspended solids tend to be stratified (Figure 3.2). Generally, levels of calcium, chloride, dissolved organics and the pH of the fluid increase remarkably with increasing fluid depth (Specken 1975). Horizontal variability between different points in the sump is also expected due to the release of the waste from one point (i.e. at the shale shaker).

Characteristics of sump contents may change with time as a result of atmospheric and leaching processes as well as human errors (e.g. accidental inflow or overflow resulting from inappropriate pit design) (Figure 3.3).

The detailed sump chemistry data are presented in Appendix C.1. The data have been classified by region, type of fluid and type of extraction procedure, where possible. It should be noted that no information was available on the sampling procedures (e.g. sampling depth, sampling location within the sump, compositing, sample handling). In many cases the extraction procedure was not stated. Also, the age of the sump was not given.

The data showed substantial variability in chemical properties between the different sumps. The variability appears to be related to the type of drilling fluid used, the drilling location and the extraction procedure (e.g. water soluble vs. acid digested determinations).

Tables 3.3 to 3.5 summarize the data for a number of selected parameters. In these tables, the maximum values were used. However, the range

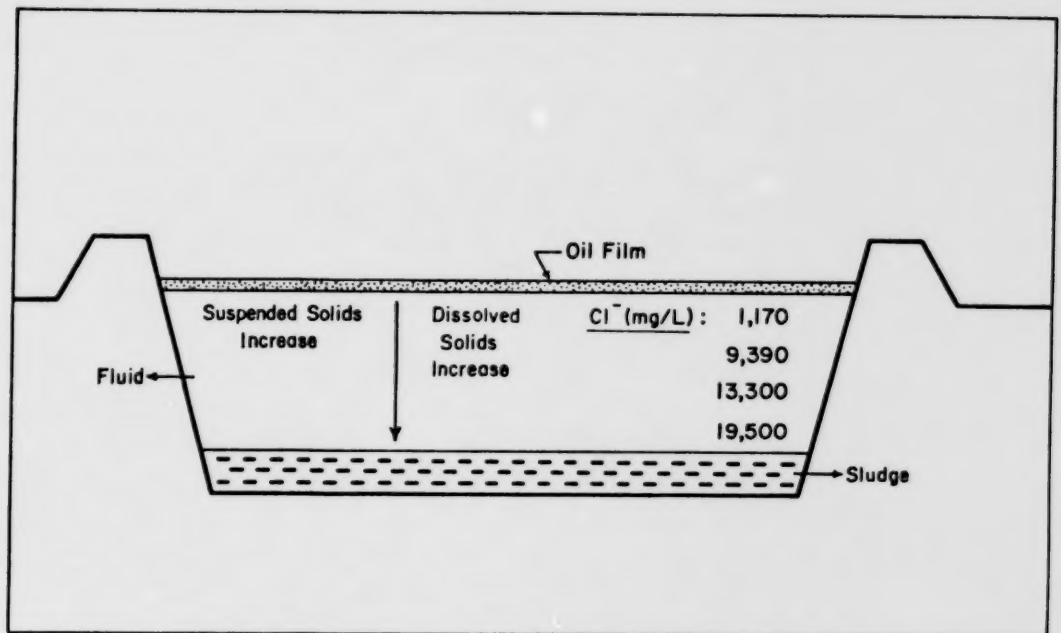


Figure 3.2 Sump Phases and Stratification. Chloride Levels Indicated are Based on Specken (1975).

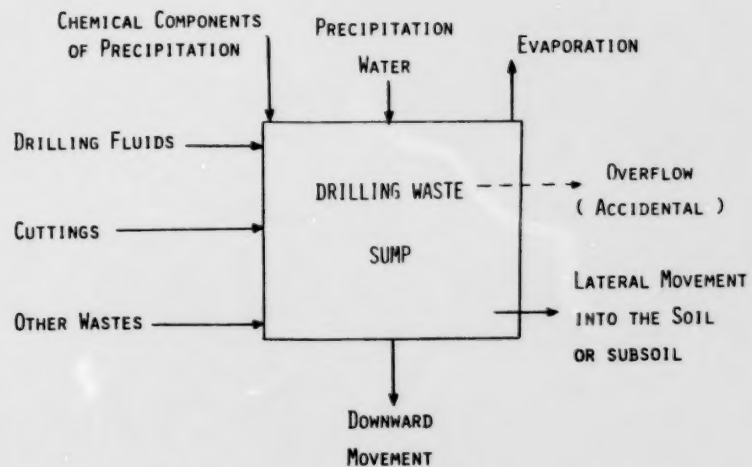


Figure 3.3 Main Sump Inputs and Outputs.

Table 3.3 Summary of the Chemical Analysis Data for the Fresh Water/Gel Sump Fluids and the Calculated Loading and Soil Concentration*.

	Composition (mg/L)**		Loading (kg/ha)		Projected Concentration (ppm)	
	Lloydminster	Kindersley	Lloydminster	Kindersley	Lloydminster	Kindersley
A. Water Soluble						
pH	11.7	9.7	--	--	--	--
EC	2000	--	--	--	--	--
SAR	144	74	--	--	--	--
Na	10100	1700	472	79.4	210	40
Cl	2700	2290	126	107	60	50
Al	8.1	0.42	0.38	<0.02	0.17	<0.01
B	3.85	4.1	0.18	0.19	0.08	<0.08
Cr	0.74	2.64	0.03	0.12	0.01	0.05
Mn	0.13	0.11	<0.01	<0.01	<0.01	<0.01
P	33	32	1.05	0.15	0.7	0.07
Zn	4.1	0.11	0.19	<0.01	0.08	<0.01
B. Acid Digested						
Al	999	815	46.7	38	20	20
B	4.4	5.3	0.2	0.25	0.09	0.11
Cr	3.1	2.27	0.15	0.11	0.07	0.05
Mn	43	90	2.0	4.2	0.9	1.0
P	153	280	7.15	13.1	3.2	5.8
Zn	27.4	132	1.28	6.2	0.6	2.7

* Only selected parameters are included here. Reference is made to the Chemical Analysis Section of the Appendices. Calculations were based on off-lease disposal rate of 247 barrels/ha (100 barrels/acre), and maximum concentrations.

** mg/L, except for pH and sodium adsorption ratio. Electrical conductivity is in millisiemens/m.

SAR = sodium adsorption ratio

EC = electrical conductivity

Table 3.4 Chemical Analysis (acid soluble) of Fresh Water/Polymer Sump Fluids and Calculated Loading and Soil Concentration*.

	Composition (mg/L)**	Loading (kg/ha)	Projected Concentration (ppm)
pH	7.3	--	--
SAR	8.3	--	--
Na	1968	92	40
Cl	876	41	20
Al	9229	431	190
B	1328	62	30
Cr	14	0.7	0.31
Mn	26	1.2	0.5
P	273	13	5.8
Zn	119	5.6	2.5

* Selected parameters for an XC polymer, for more detail see the Appendix. Calculations were based on an off-lease disposal rate of 247 barrels/ha (100 bbls/acre).

** mg/L except for pH and sodium adsorption ratio

SAR = sodium adsorption ratio

Table 3.5 Chemical Analysis (water soluble) of Salt Water Base Sump Fluids and Calculated Loading and Soil Concentration*.

	Composition (mg/L)**	Loading (kg/ha)	Projected Concentration (ppm)
pH	11.02	--	--
SAR	338	--	--
Na	90,200	4212	1870
Cl	137,400	6417	2850
Al	1.5	0.05	0.02
B	7.19	0.34	0.15
Cr	1.27	0.06	0.03
Mn	0.19	0.01	<0.01
P	3.45	0.16	0.07
Zn	0.93	0.04	0.02

* Selected parameters only, for more detail see the Appendix.
Calculations were based on an off-lease disposal rate of 247 barrels/ha
(100 bbls/acre)

** mg/L except for pH and sodium adsorption ratio

SAR = sodium adsorption ratio

and mean for all parameters considered are given in the appendices.

The freshwater/gel and salt base sumps were strongly alkaline with pH of up to 11.7. The freshwater/polymer had a near neutral pH. Electrical conductivity, a measure of salinity, data were available for only few samples. However, the levels of dissolved ions are available for most samples. The salt water base sump fluids, as expected, showed the highest level of salinity with chloride levels exceeding 130,000 mg/L. The freshwater/gel from the Kindersley area and the freshwater/polymer had the lowest salinity. The Lloydminster sumps had intermediate salinity levels.

Sodium adsorption ratio (SAR) is an expression of the activity of sodium in relation to calcium and magnesium. The freshwater/polymer had the lowest SAR values. All the other types showed a substantially higher SAR. The formulation of the latter types include additives with high sodium concentrations.

The levels of water soluble trace elements in the Lloydminster and Kindersley freshwater/gel sumps are generally similar. The salt water sumps from Estevan showed comparable values.

The freshwater/gel sumps from both the Lloydminster and Kindersley areas had considerably lower total (acid soluble) levels of aluminum (Al), boron (B) and chromium (Cr) than the freshwater/polymer. Manganese (Mn) was higher in the freshwater/gel. The levels of phosphorus and zinc (Zn) were comparable in the two types of sumps. The noted differences could not be readily explained in terms of the mud formulation. They may be related to formation differences or to chemicals added to the sump after drilling was completed.

In general, the water soluble fraction of trace elements appears to represent only a small fraction of the total concentration. Although this is based only on the freshwater/gel fluids, for which both water-soluble and acid-soluble data are available, the same relationship is expected for the other fluid types. This is mainly because of the high pH levels observed which generally reduce the solubility of trace elements.

As indicated above, the forgoing analysis was based on the maximum observed levels of the various chemical parameters regardless of how frequent they actually occur. The frequency of occurrence of the various levels of selected parameters will now be addressed. The results for surface hole¹ and sump fluids are depicted in Figure 3.4. In calculating the frequency, no differentiation was made between regions or types of fluids.

In most cases the pH was in the range of 8-10. Surface hole fluids appear to have a slightly lower pH than sump fluids.

Chloride, sodium and sulfate levels were generally lower than 1000 mg/L. However, some extreme cases with levels exceeding 10,000 mg/L were recorded. Sump fluids showed a somewhat wider range of major ions concentrations than surface hole fluids.

Total boron was mostly below 4 mg/L. Surface hole fluids showed a wider range of boron concentrations than sump fluids, indicating that the main source of boron must have been the drill cuttings.

Total nickel was lower than 8 mg/L, while total chromium was generally below 2 mg/L. In the vast majority of samples zinc levels were less

¹Surface (top) holes are usually drilled using surface water containing native solids with no or fewer additives than the main holes.

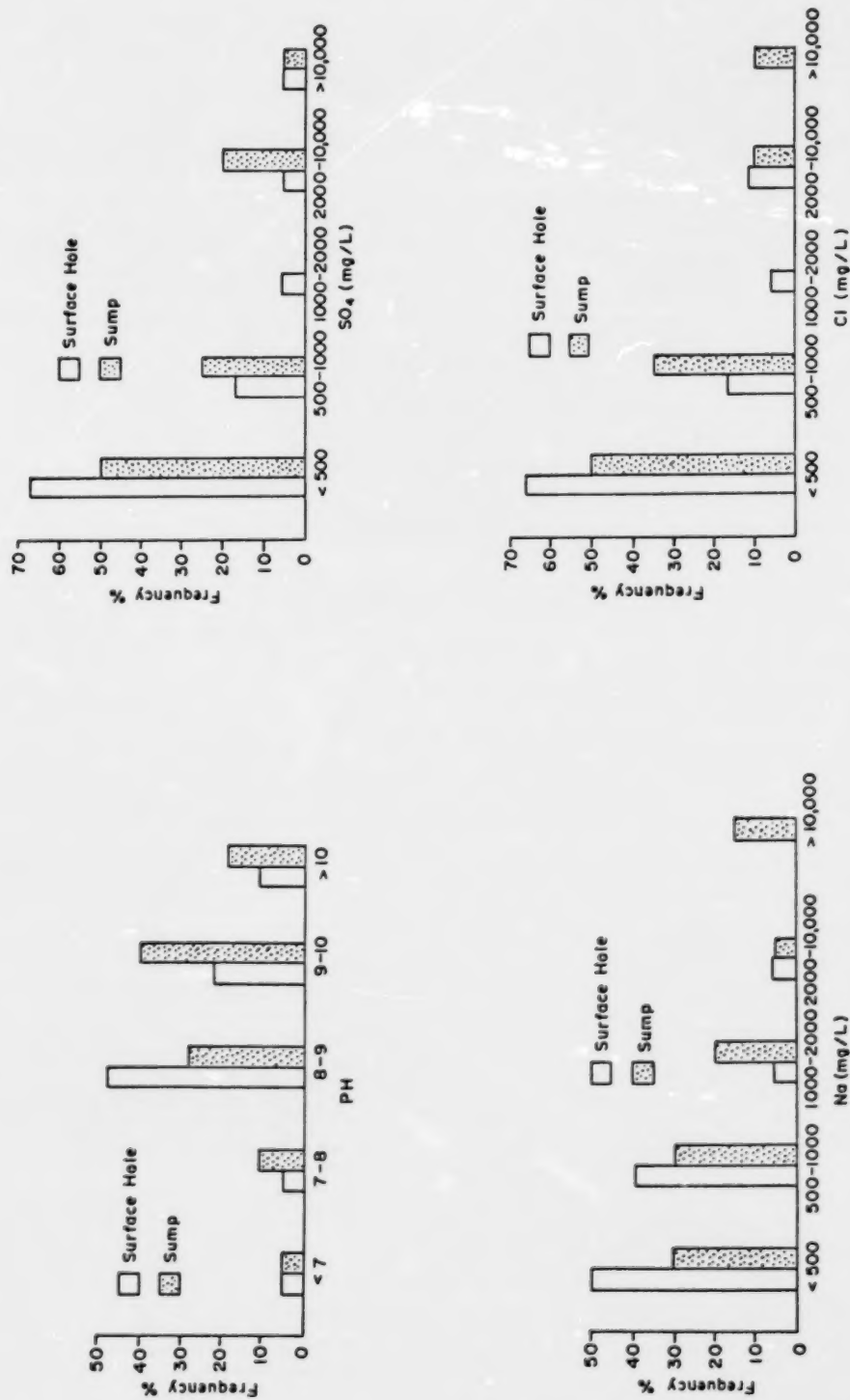


Figure 3.4 Frequency of Occurrence of Various Levels of Selected Chemistry Parameters for Surface Hole and Sump Fluids.

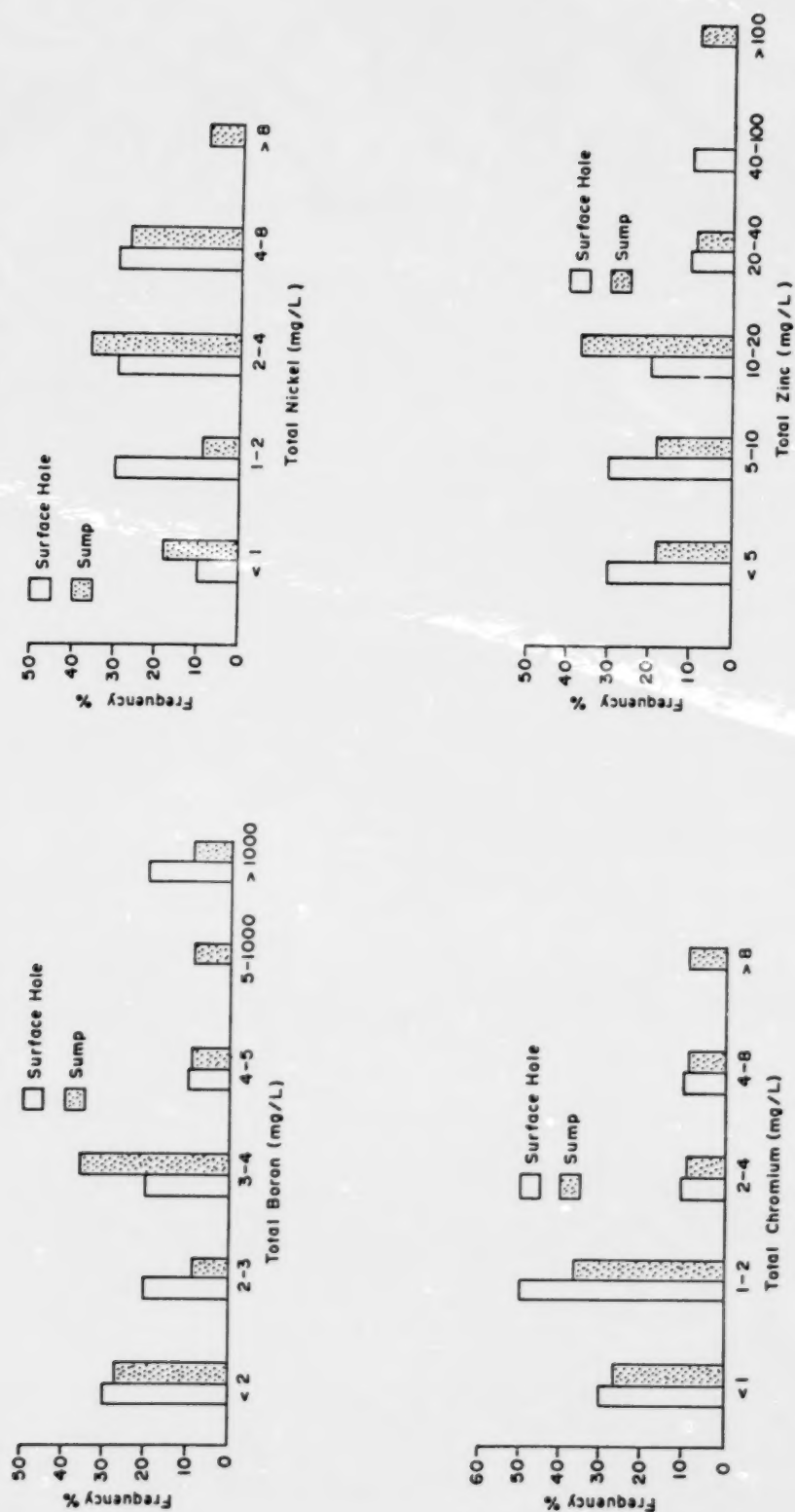


Figure 3.4 Continued

than 20 mg/L. Sump fluids had a wider range of concentrations for these elements than the surface hole fluids.

3.4 Drilling Waste Disposal Methods

Drilling waste disposal methods in Saskatchewan appear to vary with region and type of drilling fluids (Tables 3.6 and 3.7). In the Lloydminster area the most common (85% of the cases) method is spraying the liquid portion of the waste on cultivated land (fallow or stubble), or naturally vegetated areas. Normally, a vacuum truck equipped with a rotating disc or pipe spreader is used. Most respondents indicated that chemical analysis (mainly salinity and major ions) of the fluids is carried out and sump treatment is performed if the need is indicated as a result of the analysis. The main treatments include adjusting the pH by addition of sulfuric acid which could act as a flocculent, addition of other flocculents such as calcium chloride and dilution with freshwater to lower the level of soluble salts. Off lease disposal is carried out at a rate of 247 barrels/ha (100 bbls/acre). The remaining sludge portion of the waste is left to dry or solidify before backfilling of the pit.

In the Kindersley region, although the main method is spraying on cropland as described above, in more than 20% of the cases surveyed the waste was hauled for disposal in natural depressions or sloughs. In 16% of the cases, the material was disposed of on lease by squeezing the pit contents on croplands as described below.

On-lease disposal by the squeeze procedure is the most common method used in the Estevan and Swift Current areas. The spread material is left

Table 3.6 Frequency of Utilization of the Different Drilling Wastes Disposal Methods in the Oil Producing Regions in Saskatchewan.

	Frequency (%)*			
	Lloydminster	Kindersley	Swift Current	Estevan
Spray on fallow	85	64	--	21
Squeeze out of pit				
- onto cropland or natural vegetation with little clean up activities	3	--	56	76
- onto cropland with comprehensive clean up program	--	16	--	--
- onto trenches, burial	--	--	5	--
Haul to natural depressions, sloughs	4	20	39	**
Tank storage, reuse	8	--	--	--
Injection wells	--	--	--	3
Not given	<1	--	--	--

* Frequency is based on a survey of 411 wells.

** The survey did not identify this method for Estevan. However, further communication with SEM district office indicated that it is being used in this region.

Table 3.7 Frequency of Disposal Methods Used in Saskatchewan by Type of Drilling Fluid Systems.

Disposal Method	Frequency (%)*					
	1**	2	3	4	5	6
Spray on fallow	67	50				100
Squeeze out of pit						
- onto cropland or natural vegetation with little clean up activities	18	7			100	
- onto cropland with comprehensive clean up program		43				
- onto trenches, burial	1					
Haul to natural depressions, sloughs	14					
Tank storage and reuse			100			
Injection wells				67		
Not given				33		

* Frequency is based on a survey of 411 wells.

** Drilling fluid systems:

- 1 Fresh Water/Gel
- 2 Fresh Water/Polymer
- 3 KCl/Polymer
- 4 NaCl
- 5 CaCO₃
- 6 Oil Base

to dry before final clean up and grading of the site. In some cases the dried mud is returned to the pit and, then, the site is graded. Some firms respread the topsoil which was stripped and stockpiled prior to site construction. The waste application rates vary with the volume of the sump fluids and the size of the lease. The average rate is estimated to be 3800 and 6400 bbls/ha for the Swift Current and Estevan areas. Lower application rates are expected for the Kindersley area. In other cases, the waste is squeezed into specially prepared deep trenches and capped with 2.5-3.5 m of soil and subsoil material. The spray method is employed in a relatively large number of cases in the Estevan area.

Deep well injection does not appear to be a common disposal procedure in Saskatchewan.

The survey showed that none of the high salinity fluids was disposed of through the regular land application procedures. The KCl/polymer fluids were stored in tanks for reuse. NaCl fluids were disposed of by deep injection or were hauled to government-approved disposal sites.

The spray and squeeze methods are the main procedures with the other types of drilling fluids, i.e. the freshwater/gel and freshwater/polymer.

In Alberta, the disposal methods used are similar to those of Saskatchewan. However, pit burial and deep trenching are discouraged. Also, oil companies are required to submit acceptable plans for disposal of KCl fluids on crown land prior to lease construction (Lloyd 1985).

In Manitoba, the on-site standard squeeze procedure is the dominant method of drilling waste disposal.

4 ENVIRONMENTAL INTERACTIONS

4.1 General

The main environmental concerns associated with the surface disposal of drilling wastes include:

- * the potential for groundwater and surface water contamination through migration of pollutants from the reserve pit or from the receiving soil (Figure 4.1),
- * potential direct and indirect effects on crops and natural vegetation,
- * potential alteration of the chemical and physical properties of the receiving (or amended) soil, and
- * possible food chain transfer of contaminants, primarily trace elements.

The following section will assess the potential impact on the basis of knowledge acquired concerning mud formulations and the existing environment. Section 4.3 will predict the drilling waste-soil-plant interactions.

The impact and fate of land-applied drilling wastes are likely to be governed by many factors (Figure 4.1) including:

- * chemical and physical characteristics of the waste material (Section 3),
- * waste application procedures (e.g. planned vs. actual application rates, method of waste application and incorporation, timing of application) (Section 3.4),
- * physical and chemical properties of the receiving environment (Section 2),

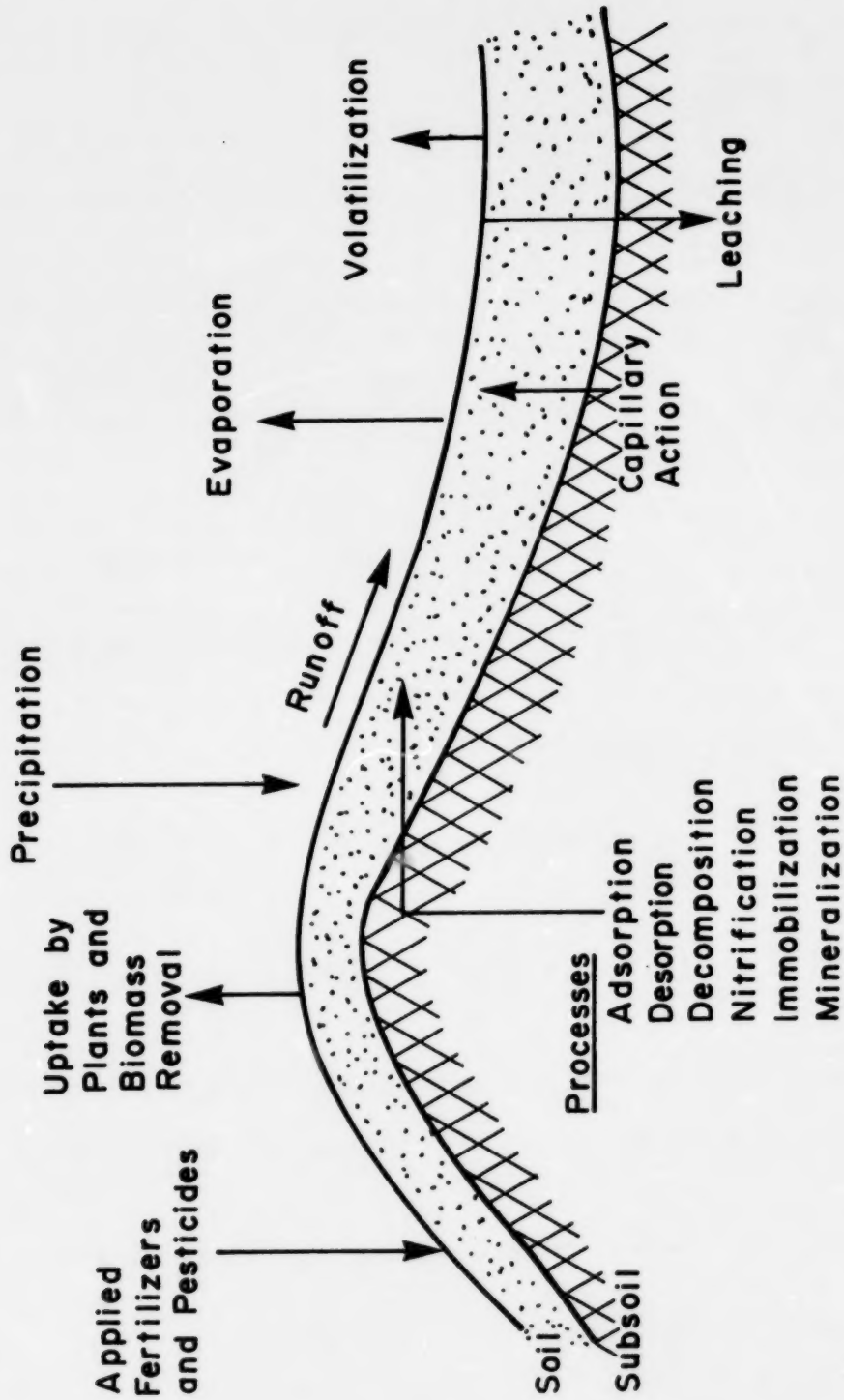


Figure 4.1 Fate of Surface-Applied Drilling Wastes.

- * site characteristics (e.g. topography, climatic conditions), and
- * agricultural practices (e.g. cropping pattern, fertilization).

4.2 Drilling Fluid Systems and Components

As can be seen from the mud formulation information (Section 3.2, Appendix C.3), drilling fluids contain some components that are potentially detrimental to plants and soils as well as others that are expected to be beneficial. The major constituent of the freshwater/gel systems is bentonite, a montmorillonite clay. Bentonite could improve the water holding capacity of sandy soils. It can also increase the cation exchange capacity, the ability of a soil to retain cations, of such soils, thus contributing to the improvement in the soil nutrient relations. On the other hand, bentonite could interfere with the infiltration and permeability of fine textured soils, particularly those with high sodium concentration.

Soluble salt additives are used in various amounts in almost all the common drilling fluids used in Saskatchewan. Application of such fluids will result in an increase in total soil salinity as well as in the concentration of the specific ions added. These changes may have unfavourable effects on plants. Salinity can affect plant growth through a reduction in soil water potential, thus reducing the ease with which plants can absorb soil water. In addition, plant toxicity and nutrient imbalances can result from high concentration of certain ions, i.e. specific ion effect. If sodium predominates, plants can be affected indirectly as a result of deterioration in soil physical conditions.

Plant species, and even varieties of the same species, vary in their

response to salinity (Figure 4.2). It should be noted that yield reduction is gradual and there is no clear-cut threshold of salinity tolerance. The response to salinity may be modified somewhat depending on such factors as salinity changes with depth and time, and soil chemical and physical properties and climatic conditions.

High levels of certain ions such as sodium and chlorides can cause specific ion effects. Chlorides are more damaging to plants than sulfates and sodium is slightly more damaging than potassium. Sodium and chloride are highly mobile ions in the soil. Leaching of these ions will take place at least during years of high precipitation, provided that internal drainage is adequate. Potassium is relatively immobile.

Sodium, if introduced in large amounts, can replace the existing cations (such as calcium and magnesium) in the soil. An exchangeable sodium percentage exceeding 15 would weaken the stability of soil aggregates causing dispersion and swelling. This, in turn, would decrease the macropores and, thus, sharply reduce permeability (Figure 4.3). The amount of soluble salts present modifies this relationship (Figure 4.4).

As indicated in Section 3, there are several sources of trace elements in mud additives. Trace element availability for plant uptake and toxicity varies with soil pH, soil cation exchange capacity, amount of waste applied, concentration and form of the element and plant species and varieties. However, soil pH appears to be the most important single factor. Many heavy metals tend to form insoluble complexes in high pH environments.

Natural herbaceous vegetation can develop tolerance to heavy metals in a relatively short period of time (few years). This tolerance, how-

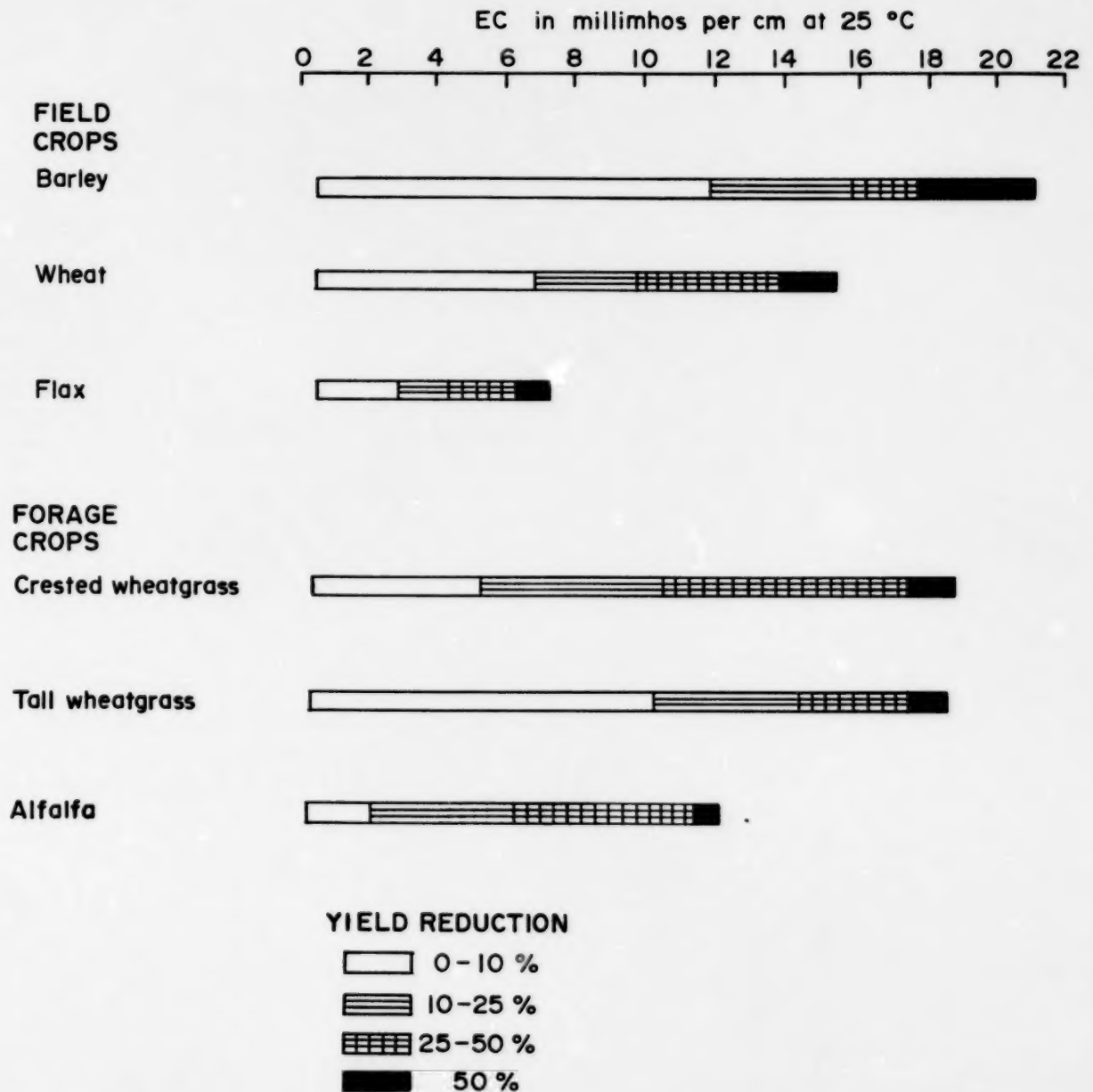


Figure 4.2 Response of Selected Crops to Salinity (Based on Bernstein 1964 and data from Salinity Program of Saskatchewan Department of Agriculture).

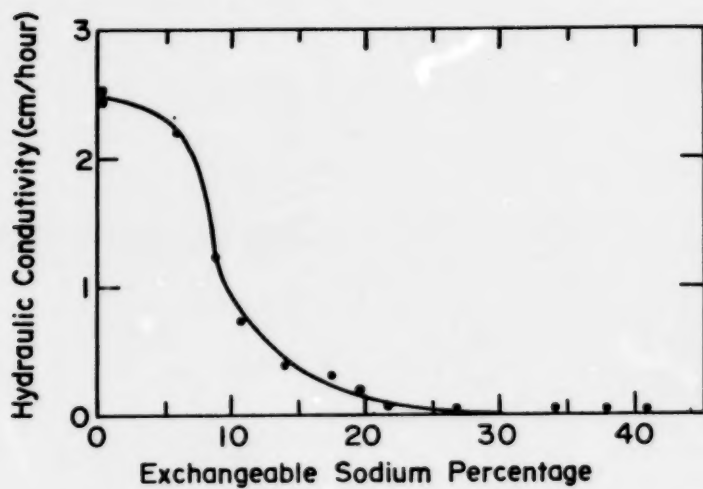


Figure 4.3 Relationship Between Exchangeable Sodium Percentage and Soil Hydraulic Conductivity.

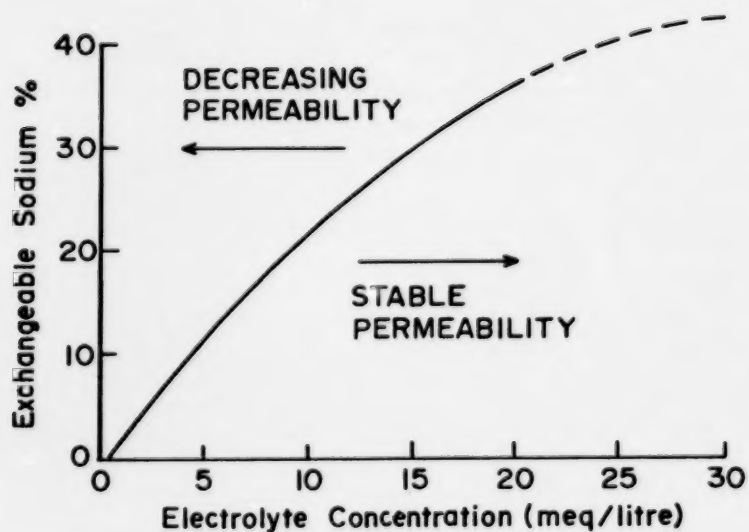


Figure 4.4 The Effect of Salt Concentration on the Relationship Between Exchangeable Sodium Percentage and Soil Permeability.

ever, is metal specific.

Some of the drilling additives contain a number of essential plant nutrients, e.g. phosphorous in acid pyrophosphate, potassium in KCl and sulfur in K_2SO_4 . A beneficial effect from these additives would depend on the amount applied and the status of these nutrients in the soil.

Several of the additives are of plant origin such as plant fibers, starches and sawdust. These materials are not expected to be toxic to plants and may even improve the physical conditions of the soil. Soil microorganisms are capable of decomposing these materials. However, temporary immobilization of nutrients, such as nitrogen, may occur as a result of microbial activities.

The polymers used in the formulation of drilling fluids are similar to those used as agricultural conditioners. These materials are not expected to be detrimental to plants because of their high molecular weight which prevents them from entering the plants. Zitco (1975) indicated that these materials may undergo some reactions during the drilling process resulting in products that have higher toxicity than the parent compounds. However, there are indications that the majority of the organic constituents end up in the sump as unaltered mud additives (Stroscher 1980).

Of the hydrocarbons used as mud additives only diesel oil is expected to have detrimental effects. Nevertheless, the materials in diesel oil are volatile and degradable and should be dissipated within months or few years. The main effect of crude oils appears to be related to reduced soil aeration and temporary immobilization of plant nutrients, particularly nitrogen. The direct effects of oils on plants are not clear.

Paraformaldehyde is used as a preservative to prevent biodegradation of the organic additives. The main concern is the possible effect of this bactericide on soil organisms. However, paraformaldehyde is rated low in the toxicity scale and is naturally degradable in the soil (Robichaux 1975).

A review of the studies dealing with the effects of individual drilling fluid components is given in Appendix D.1. These studies were also summarized in a tabular form in Appendix D.2a. The results agree, in general, with the effects predicted on the basis of the chemical and physical nature of the additives as discussed above. However, the toxicity reported for some organic additives like starch could not be explained.

The lowest rates used in those studies were comparable to the on-lease application rates in Saskatchewan, but were several orders of magnitude greater than the off-lease rates. For example, at the 1:4 mud-soil ratio (the lowest application rate), the calculated soil concentration of potassium chloride, iron chromelignosulfonate and plant and synthetic fiber mix is 22.7, 6.8 and 11.4 g/kg of soil, respectively. The corresponding maximum concentrations expected in an off-lease disposal conditions in Saskatchewan are 2.6, 0.15 and 0.01 g/kg of soil, respectively (Tables 3.2, 4.1 and Appendix C.3).

Since the soil-plant system reacts to combinations of these components rather than individual additives, a number of studies investigated the effects of synthesized complete drilling fluids on plants and soils (Appendices D.1 and D.2b). Both beneficial and detrimental effects, as indicated in the above analysis, were reported. The effects varied with the soil type and the drilling fluid system. However, salinity and

Table 4.1 Maximum Projected Soil Concentrations (g/kg) of the Various Components Used in the Formulation of Some of the Less Commonly Used Drilling Fluid Systems*.

Components	Fresh Water/ Polymer	KCl Polymer	NaCl
Acrylamide		0.08	
Aluminum stearate			**
Bentonite		1.0	
Calcium carbonate	0.08		
Calcium sulfate	0.05		
Hydroxyethyl cellulose			<0.01
Polysaccharides	0.04	0.05	0.55
Polyanionic cellulose	<0.01		
Potassium chloride		2.62	
Sawdust	0.01		
Sodium acid pyrophosphate		0.01	
Sodium carbonate	0.05		
Sodium carboxymethyl cellulose	0.04		
Sodium chloride			6.3
Sodium hydroxide		0.05	
Starch	0.03		
Xanthan gum	<0.01		

* Based on an application rate of 247 barrels/ha (100 bbls/acre). See the Appendix for detail.

** Additive used but amounts were not released.

sodicity appeared to be the dominant causes of reduced plant growth and germination. Zinc, chromium and organic toxicities were suspected in a few cases. Improved growth appeared to be related to increased nutrient availability or improved soil physical condition in an acidic, sandy loam soil.

The above studies dealt with individual components and synthesized fluids under greenhouse or growth room conditions. Extrapolation from those studies to field conditions employing drilling wastes (i.e. sump fluids) would be difficult. Nevertheless, those studies have substantially improved our understanding of the cause and effects relationships which are often difficult to determine under field conditions. Also, the knowledge gained would be useful in assessing the impact of on-site accidental spills of individual components.

4.3 Drilling Wastes

The sump fluid chemistry data confirm, in general, the impacts predicted on the basis of mud components and formulations (Section 4.2), i.e. the primary parameters of concern are salinity and sodicity. It appears, though, that additional salts and trace elements may have been picked up during the drilling operation.

The fluid chemistry data were used to predict soil concentrations of the major ions and trace elements (Tables 3.3, 3.4 and Appendix C.4). These calculations were based on present off-lease disposal maximum application rates of 247 bbls/ha (100 bbls/acre).

The high pH levels are not likely to have any direct detrimental effects on plants. The pH of the amended soil may be raised somewhat, but

the equilibrium level will likely be much lower than that of the waste. Most plants grow normally at pH levels as high as 8.5-9.0. The pH, however, affects the availability of soil nutrients (Figure 4.5). For example, copper and zinc availability decreases with increasing soil pH. Also, phosphorous availability is reduced in the pH range of 7.0-8.5.

The effects of high sodium adsorption ratio on soils have been discussed in the previous section. The magnitude of the impact depends on the equilibrium levels of exchangeable sodium (exchangeable sodium percentage) in the amended soil. This is a function of the physical and chemical characteristics of both the waste and the receiving soil. However, a rough estimate can be made for a medium textured, nonsaline, non-sodic soil on the basis of empirical data (U.S. Salinity Laboratory Staff 1954). An SAR of 12 for the waste would result in an exchangeable sodium percentage (ESP) of 15 above which sodium starts to interfere significantly with soil physical characteristics. An SAR of 18 constitutes a high sodium hazard. The calculated SAR for most of the sump fluids considered in this study indicate a significant increase in the ESP of the soil.

Based on the sump fluid chemistry data almost all fluids would result in an increase in soil salinity. The least increase would be expected from the freshwater/polymer, followed by freshwater/gel. At an off-lease application rate these fluids would increase salinity only slightly and no significant yield reduction could be expected from salinity alone. Additions of up to 11.2 t/ha of potash dust to a silt loam or loam soil in Saskatchewan did not affect crop yield (Ballantyne 1974). On-lease disposal rates would result in a greater increase in salinity

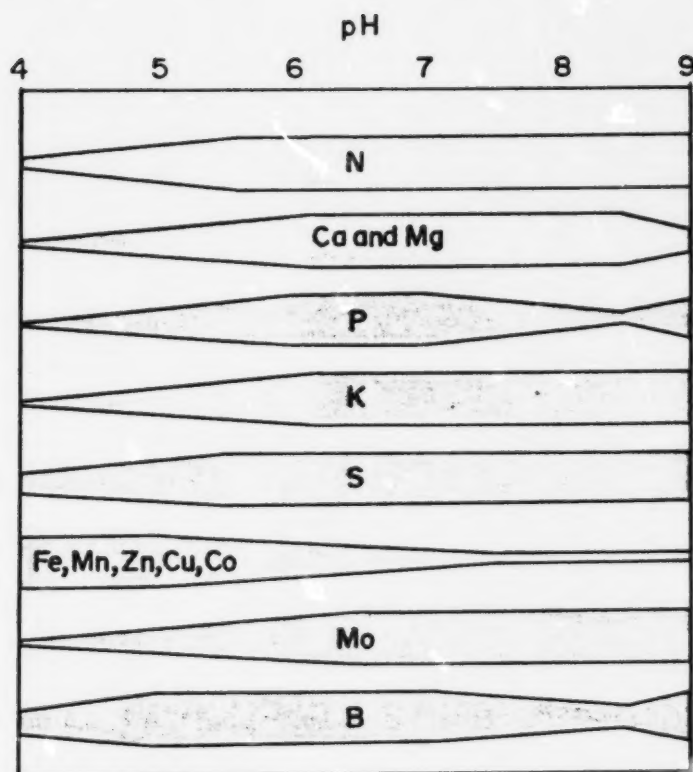


Figure 4.5 Effect of pH on Nutrient Availability
(modified from Buckman and Brady 1969).

and yield reduction will depend on the indigenous soil salinity levels and crop sensitivity to salinity (Figure 4.2).

Salt base fluids represent the highest salinity hazard for both on-lease and off-lease disposal. A significant reduction in germination and yield of sensitive and moderately tolerant species would be expected, even if original soil salinity levels were low.

The critical level of chloride in sand and water culture varies from 800 mg/L for alfalfa to 3500 mg/L for barley. In soils, however, plants can tolerate much higher levels, e.g. ranging from 1800 mg/L for flax to 5900 mg/L for barley (Chapman 1966). More than 85% of the sump fluid samples contained chloride ion levels of less than 1000 mg/L. The highest chloride levels were associated with the salt base fluids and are considered much above the critical level at both on-lease and off-lease disposal rates. As indicated earlier the chloride ion is easily leachable from the root zone.

The majority of samples had a sulfate level below 1000 mg/L. This, in itself, is not sufficient to cause plant growth reduction. Sulfates are less damaging to plants than chlorides.

Trace element concentrations in many drilling waste samples exceed the water quality standards developed by Environment Canada and other jurisdictions for irrigation purposes (Appendix D.2c). It should be noted, however, that these standards are intended for repeated application while drilling waste disposal is often a one-time application.

A comparison between trace element levels in drilling waste and in commercial fertilizers revealed that, with few exceptions, the levels in drilling wastes are comparable to or lower than those in commercial fer-

tilizers (Table 4.2).

Total trace element concentrations in the sump fluid samples are substantially lower than those for sewage sludges as reported by Graveland (1979) for seven locations in Alberta and by Van Loon (1974) for ten locations in Ontario. Sewage sludges are frequently applied to agricultural land for fertilization purposes.

Concerns over possible environmental problems resulting from the application of sewage sludges to agricultural land have prompted numerous studies on the metal pollution potential of these materials. The accumulated data have provided the basis for the development of sludge application procedures, including the establishment of a maximum permissible loading (MPL) for trace elements (Table 4.3). With the exception of boron, maximum calculated loadings for off-lease disposal are well within the MPL (Table 4.3). For elements with no established MPL, their concentrations can be compared with the levels found in normal (nonpolluted soils) included in the same table. This revealed that the amounts added represent only a small fraction of the amount found naturally in the soil.

The trace element loading for on-lease disposal can be obtained by multiplying the off-lease values by a factor of 14 to 28 depending on the size of lease and the amount of waste generated. Under the on-lease disposal, the levels of boron, manganese and molybdenum exceeded the MPL for sludge application. It should be noted, also, that on-site disposal involves spreading of the drilling waste sludge on the land. It is suspected that these sediments contain higher levels of trace elements.

Recent work (Deely and Canter 1985) indicated that trace elements are held strongly within the drilling waste sediments due to the high pH

Table 4.2 A Comparison of Heavy Metal Concentrations in Commercial Fertilizers and Maximum Levels in Drilling Wastes.

Metal	Concentration		Percentage of Times Fertilizer Levels were Exceeded
	Fertilizers (ppm)*	Sump Fluids (mg/L)**	
Cd	2.1 - 9.3	1	0
Co	4 - 5	4	0
Cr	39 - 92	14	0
Cu	2.4 - 3.1	13	35
Fe	5,700 - 11,800	5270	0
Ni	23 - 39	12	0
Pb	2 - 3	49	15
Zn	42 - 108	119	8

* Based on Whitby et al (1977) for monoammonium phosphate (12.5-50-0), diammonium phosphate (18-46-0), superphosphate (0-20-0) and triple superphosphate (0-46-0).

** Represent the highest level found in this study (Appendix C.4).

Table 4.3 Concentration of Trace Elements in Normal (noncontaminated) Soils and Maximum Permissible Loading.

Elements	Normal Soils (ppm)	Maximum Calculated Loading (kg/ha)*	Maximum Permissible Loading** (kg/ha)
As	0.1 - 40	--	2 - 15
B	2 - 100	62	4.5 - 10
Ba	70 - 5000	--	--
Be	1 - 40	0.09	--
Cd	0.01 - 7	0.2	0.1 - 20
Cr	5 - 3000	0.7	4 - 1000
Co	1 - 40	0.19	0.25 - 30
Cu	2 - 100	0.61	15 - 500
Pb	2 - 200	2.3	1.5 - 2000
Mn	100 - 4000	4.2	10
Mo	0.2 - 5	0.5	4
Ni	10 - 1000	0.6	2 - 2000
Se	0.1 - 2.0	<0.01	2.4 - 5
Sr	50 - 1000	2.02	--
V	20 - 500	1.6	--
Zn	10 - 300	5.6	50 - 1000

* Maximum calculated loading is based on the highest concentration found in this study and assuming a land application rate of 247 bbls/ha (100 bbls/acre).

** Over a 30 year period, source: several reports (see the Chemical Analysis Section of the Appendix).

-- No values found.

and alkalinity conditions. However, the availability of these elements for uptake by plants may increase as a result of the more acidic conditions in the soil, particularly in the northwestern region of the province.

The foregoing analysis pertains to waste application to fallow or stubble fields. Where disposal operation involves spreading of the drilling waste on naturally vegetated areas such as grasslands, there is a potential for direct effects on foliage as a result of exposure to the waste. The main effect would be damage to plant tissues (chlorosis and or necrosis) in the case of highly saline waste. Herbaceous plants, particularly grasses and grass-like plants, are less sensitive to this type of exposure than woody plant species. Another direct effect is possible reduction in photosynthesis resulting from the formation of a film on the leaf surfaces.

The response of natural vegetation to waste application differs from that of crops in another aspect. The alteration of the natural vegetation environment as a result of drilling waste application could trigger a change in species composition. Species that are more adapted to the new environment would be introduced or increase in importance (e.g. salt tolerant species in newly salinized areas).

Air photo interpretation of selected drilling sites in the Estevan area showed varying degrees of revegetation success. Some of the sites examined were several years old with little vegetation cover. Others appeared to have an adequate cover.

Available soil analysis data for a number of reclaimed drilling sites in Virden, Manitoba (Dunning 1985) showed a slight increase in the

fine fraction of the soil, a general increase in available nitrogen and a decrease in available phosphorous. The amended soils have a pH of 7.3 to 8.0 and electrical conductivity ranging from 0.4 to 2.7 mmhos/cm, i.e. nonsaline to slightly saline soils.

A review of the studies dealing with the effects of drilling wastes on plants and soils is given in Appendix D.1. These studies were also summarized in a tabular form in Appendix D.2d. The results agree, in general, with the foregoing analysis. The effects varied with the type of waste, rate of application and plant species. Salinity and sodicity appeared to be the main causes of reduced germination and plant growth. Potassium chloride fluids were most damaging, but growth reduction occurred with some freshwater systems, particularly at high rates of application (several thousand barrels/ha). The levels of some trace elements in both soils and plants were elevated but were not considered a problem in terms of plant growth, particularly under field conditions, or in terms of food chain transfer. Boron status was not considered in any of these studies. Some beneficial effects from low rates of application were reported for some coarse and medium textured soils. The review revealed that only two comprehensive field studies were carried out using sump fluids. One of those studies dealt with a forest vegetation in the Foothill Region of Alberta and the other involved arid grassland in Wyoming.

5 MITIGATION MEASURES

The objectives of mitigation are to minimize the impact on the environment and to restore the impact area to a productivity level that is similar to or greater than the original level, as soon as practically possible. Mitigation measures can be implemented during the following phases:

- * planning and construction,
- * operation (drilling) phase, and
- * pit closure and reclamation phase.

5.1 Planning and Construction

Toxicity of drilling fluids could be reduced through the selection of the less toxic mud systems and components, whenever possible. This should have little, if any, effect on the cost of drilling since drilling fluids represent only a small fraction of the total cost of the drilling operation and that the less toxic additives may not necessarily be more expensive.

It is understood that, in some cases, the drilling fluid options may be rather limited (e.g. formation characteristics requiring saturated salt or oil base systems). In such cases, emphasis in the planning should be on reuse of such fluids, minimizing volume of waste generated, separating the freshwater fluids from the highly saline wastes and disposing of the potentially detrimental fluids by other means (e.g. subsurface disposal through deep well injection or use of approved waste disposal sites).

In areas where there is a potential for surface or subsurface water contamination (e.g. known groundwater recharge areas), emphasis should be

placed on proper construction and siting of pit, including proper pit and dyke design, use of clay or PVC liners, siting the pit as close to the borehole as possible, and taking site topography into consideration in the preparation of the site layout.

Prior to site construction, the "topsoil" should be stripped and stockpiled for future use. Topsoil is defined here as surficial material that is considered suitable for plant growth and not necessarily what is termed A horizon in soil science.

5.2 Operation Phase

During the drilling operations the impact could be reduced through:

- * minimizing spills of drilling fluid additives and wastes,
- * minimizing volume of waste generated by maintaining proper solid control,
- * enforcing good housekeeping rules,
- * avoiding the release of other wastes to the reserve pit, and
- * recycling of fluids (see for example Bergh 1985; Becker 1985 and Byrd 1985).

5.3 Closure and Reclamation Phase

This phase should commence as soon as the drilling rig is released. Proper disposal planning requires knowledge of the chemical and physical characteristics of the waste and the potential receiving soil. In characterizing the waste, the following parameters should be determined:

- (1) electrical conductivity, (2) total dissolved solids, (3) chloride ion concentration, (4) sulfate ion concentration, (5) SAR, (6) pH, (7) boron,

and (8) selected heavy metals (chromium, zinc, manganese and molybdenum). Sump fluid treatment requirements and application rates can then be determined on the basis of the above data. Sampling and analysis procedures are discussed further in Appendix E.1.

To reduce sodium concentration to acceptable levels (e.g. $<70\%$ of the cations or SAR <18), sump fluids should be treated with the appropriate chemical additives (e.g. calcium sulfate). Calcium requirements may be calculated using the equations given in Appendix E.2. Sump treatment was discussed recently by Specken (1985).

Minimum acreage required for spreading of the waste may be calculated as indicated in the following section.

Prior to spreading drilling fluids, tillage of agricultural land is desirable. This would facilitate incorporation of the waste. Areas with slopes less than 8% are preferred. Areas with slopes exceeding 20% must be avoided due to the difficulty in maintaining a reasonably uniform application rate and the potential for soil erosion. Also, areas with fine textured soils should be avoided.

If the sump contents, or the remaining sludge, are to be squeezed onto the site, the land should be ripped first to facilitate incorporation of the material. Dykes should be built to confine the waste to the planned disposal site. After the spread material is dry, the topsoil should be respread evenly on the graded site. If the sludge is to be retained in the pit, it must be left to dry sufficiently or solidified using such additives as cement kiln dust, cement or other materials (for details see Loudon and McGlothlin 1975; and Musser and Smith 1985). This is necessary to reduce future land subsidence and local drainage problems.

In North Dakota, blowing of native soil into the pit is used to solidify the sump contents (Murphy 1984). Burial in deep trenches should be avoided because of the higher potential for subsidence.

Revegetation of the lease should be attempted as soon as practically possible. Where salinity problems are expected, use of salt tolerant plant species (e.g. altai wildrye, Russian wildrye, western wheatgrass) are recommended. Proper fertilization should be based on soil tests. Where sodicity exists, such as in older sites and spill sites, the appropriate amendments should be incorporated into the soil prior to revegetation. Several types of amendments are available including gypsum, calcium chloride and calcium nitrate¹ (Appendix E.3). Incorporation of organic amendments (e.g. hay and straw) would facilitate the reclamation process. The use of salt and drought tolerant species is again recommended. The land can be returned to field crop production after the exchangeable sodium percentage drops to below 15. It should be pointed out, however, that reclamation of the highly sodic soils under semiarid conditions is expected to be a slow process.

¹ Calcium chloride and calcium nitrate are highly soluble and may pose groundwater contamination problems.

6 GUIDELINES AND REGULATIONS

Most oil producing provinces and states have developed guidelines dealing specifically with drilling waste disposal. The different guidelines vary considerably in the level of detail and in emphasis. The main concerns addressed, however, can be summarized as follows:

- * potential groundwater contamination,
- * potential for surface water contamination, and
- * potential effects on crops, vegetation and soils.

This report examines the guidelines pertaining to the latter concern.

While land application of drilling wastes is entirely prohibited in some cases (e.g. Alaska), most jurisdictions allow surface application of at least the liquid portion of waste, provided that the materials meet certain quality criteria. A comparison of the quality criteria from several jurisdictions, including Saskatchewan, is presented in Table 6.1. The pertinent approval guidelines in effect in Saskatchewan, Alberta and North Dakota are given in Appendix F.

The North Dakota guidelines emphasize site planning and reclamation and groundwater protection. The Manitoba and Saskatchewan guidelines appear to have been based, at least partly, on the Alberta guidelines. However, Alberta is the only jurisdiction requiring a toxicity test. The Alberta test is intended for aquatic toxicity assessment and involves a 96 hour trout survival test.

In Saskatchewan, a maximum application rate of 247 bbls/ha (100 bbls/acre) is allowed in off-lease disposal. In Alberta, on-site disposal is allowed to a maximum of 6000 bbls. Higher rates could be considered on an individual basis. In that province, a maximum loading of 448 kg/ha

Table 6.1 Drilling Fluids Quality Criteria for Saskatchewan and Other Jurisdictions.

Jurisdiction	Maximum Application Rates	Total Dissolved Solids (mg/L)	Chloride (mg/L)	SO ₄ (mg/L)	pH	SAR	Others
Saskatchewan (On-lease) (Off-lease)	-- 100 bbls/acre	-- 4000	-- 1000	-- 2000	-- 5.5 - 8.5	-- --	
Alberta (On-lease) (Off-lease)	6000 bbls/lease (a)	-- 4000	-- 1000	-- 2000	-- 5.5 - 8.5	-- --	+ a 96 hour trout survival test
Manitoba (On-lease)	2000 bbls/lease (700 bbls/acre)	--	2000	--	5.0 - 10.0	--	
Louisiana	--	--	--	--	6.0 - 9.0	12 - 20	maximum electrical conductivity of 4-8 mmhos/cm. Also, trace element levels similar to sludge guidelines. Oil and grease 1%.
Oklahoma	(a)	3000	1000	--	6.5 - 9.0	--	Chromium (total) 0.2 mg/L, oil and grease 30 mg/L, Na 750 mg/L.
France	--	--	--	--	5.5 - 8.5	--	Suspended solids 30 mg/L, nitrogen 10 mg/L, COD 120 mg/L, oil 5 mg/L.

(a) Calculated according to equations discussed in the text.

Sources: Saskatchewan Energy and Mines, Alberta Energy Resources Conservation Board, Manitoba Energy and Mines, Crabtree (1985), Oklahoma Water Resources Board, Tramier (1982).

(400 lbs/acre) of chloride is proposed (Lloyd 1985). The value could be used to calculate the minimum acreage required for disposal as follows:

$$AR = \frac{C \times 350 \times B}{400 \times 10^6}$$

Where AR = minimum acreage requirement, (acres)

C = chloride ion concentration in ppm

B = fluid volume in barrels

In Oklahoma, two formulas are used. One of these emphasizes both terrestrial and aquatic toxicity. The larger of the two values are specified on the discharge authorization:

$$(1) AR = \frac{C \times 0.00035 \times B}{5 \times d}$$

$$(2) AR = D \times B \times 0.43 \times 10^{-6}$$

Where AR = minimum acreage requirement, (acres)

C = chloride concentration in mg/L,

d = distance (feet) to the static groundwater level,

D = total dissolved solids, and

B = number of barrels

Based on chloride concentration of 1000 mg/L, the above equations indicate that the Saskatchewan maximum application rate of 247 bbls/ha (100 bbls/acre) is much more conservative compared to other jurisdictions. According to those equations, a disposal rate in the range of 1430-2800 bbls/ha (580-1140 bbls/acre) is acceptable, assuming a chloride concentration of 1000 mg/L.

Most jurisdictions specify a maximum chloride level of 1000 mg/L, a pH range of 5.5-8.5, and a maximum total dissolved solids of 4000 mg/L,

as does Saskatchewan. However, additional criteria have been set by other jurisdictions (e.g. Louisiana, Oklahoma and Michigan). These include certain trace elements, oil and grease (Table 6.1).

7 CONCLUSIONS

In this study, the potential drilling waste-plant/soil interactions have been assessed through the analysis and integration of information collected from various independent sources. In this section, the results of this assessment are integrated further in the form of generalizations and conclusions with particular emphasis on the Saskatchewan conditions.

7.1 General

(1) Large volumes of waste (approximately 12.7 million barrels) are being generated annually as a result of drilling for gas and oil in Saskatchewan. A significant land area (22,500 ha or 55,600 acres) is required yearly for the disposal of the generated waste. Most of the potential receiving areas is productive agricultural land.

(2) Land application of drilling wastes can affect seed germination; plant growth, yield and cover; and soil physical and chemical properties. However, the magnitude and direction (negative or positive) of the impact vary with:

- * chemical and physical characteristics of the drilling waste,
- * rate of waste application,
- * chemical and physical properties of the receiving soil,
- * type of vegetation and crops, and, possibly,
- * climatic conditions.

7.2 Drilling Waste Characteristics

(3) The physical and chemical characteristics of drilling wastes are highly variable. This variability appears to be related to:

- * type of drilling fluid system(s) used;
- * type of geological formation penetrated;
- * drilling depth;
- * age of the sump;
- * type and amount of wastes, other than spent drilling fluids, and cuttings, discharged into the reserve pit;
- * sump treatment; and
- * sampling techniques, sample handling, and analytical methods.

7.3 Environmental Interactions

(4) The relative detrimental effects of the main drilling fluid systems can be ranked, in order of decreasing detrimental effects, as follows:

- * salt base systems (e.g. potassium chloride, sodium chloride),
- * diesel oil systems, and
- * freshwater systems (e.g. freshwater gel)

(5) The vast majority of the drilling fluid systems, particularly those disposed of by land spreading, are of the freshwater type, which is least detrimental to plants and soils. However, a great deal of variability in characteristics is evident among the different freshwater sumps.

(6) A one-time application of freshwater drilling wastes to agricultural land and naturally vegetated sites at the rate recommended by the Saskatchewan Energy and Mines (247 barrels/ha or 100 bbls/acre) is unlikely to result in significant reduction in plant growth or yield, or significant changes in soil properties.

(7) Present on-site disposal rates and practices could, in many cases, result in significant reduction in plant cover, growth and yield and in significant alteration of soil chemical and physical properties. The effects could be of temporary or long-term nature, depending on waste and site characteristics and site closure measures.

(8) The available information enabled a qualitative estimate of the relative sensitivity of a number of soil and site attributes to drilling wastes (Figure 7.1). This scale could be used, in conjunction with site specific information, to provide a preliminary assessment of the potential impact of drilling waste disposal from a given sump.

(9) Under certain conditions (e.g. coarse-textured, acidic soils), low application rates of freshwater/gel drilling wastes may be beneficial to plants and soils.

(10) The apparent beneficial effects associated with some cases of land application of freshwater systems may be related to:

- * increased soil water holding capacity,
- * improved soil structure,
- * raised pH, and
- * improved soil nutrient status.

(11) The main drilling waste parameters of concern appear to be:

- * salinity and specific ion content,
- * sodicity,
- * trace element content,
- * unidentified factors (organic toxicity?)

(12) Under field conditions, salinity and/or sodicity account for most of the detrimental effects.

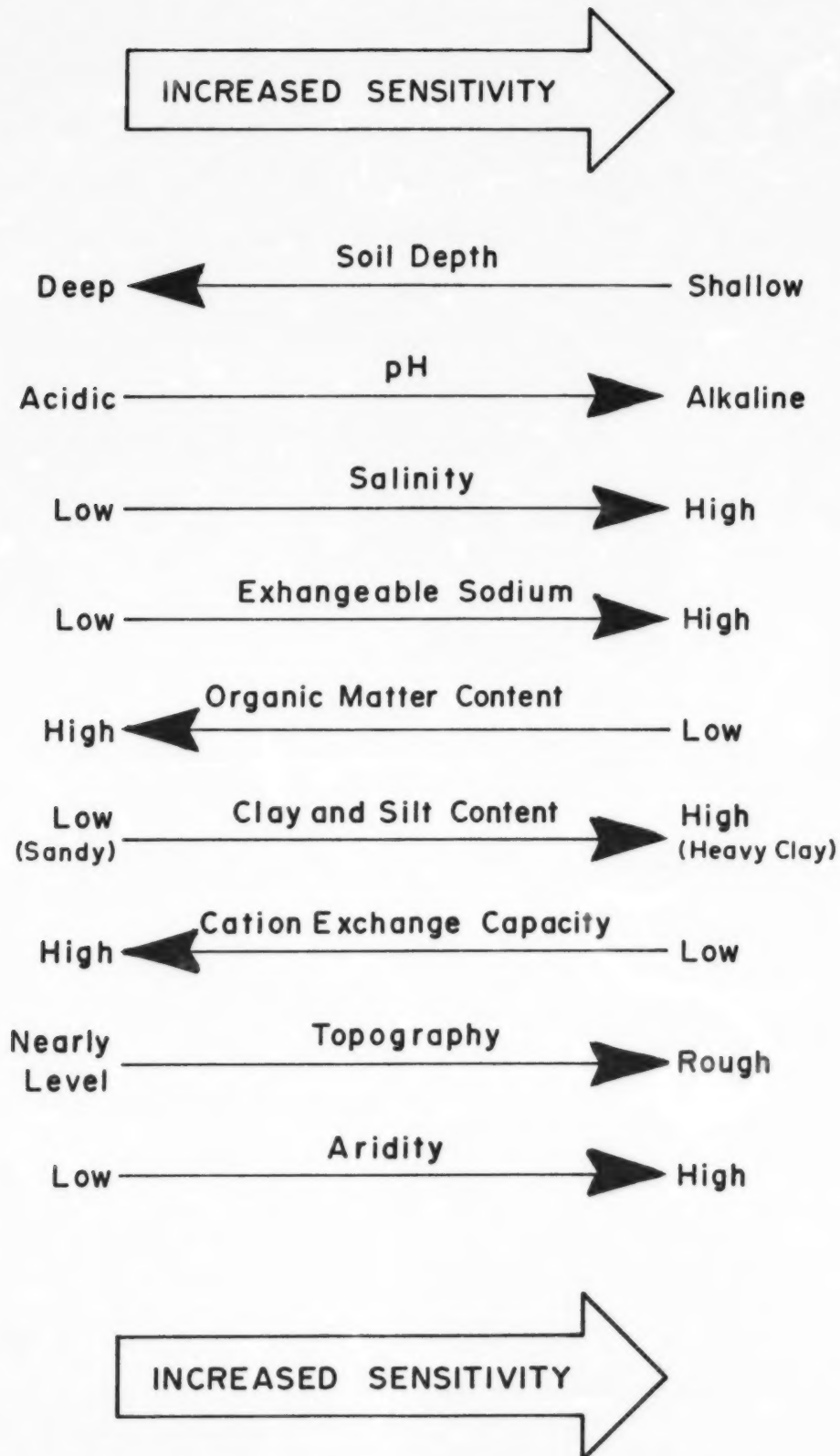


Figure 7.1 Generalized Relative Sensitivity Rating of Selected Site and Soil Attributes to Drilling Waste Application (see Appendix G).

(13) Present on-site application rates of drilling wastes could result in elevated levels of certain trace elements (mainly B, Cr, Mo, Mn and Zn) in the soil. The significance of this change, in terms of plant toxicity, may be somewhat masked by:

- * the binding ability of the soil,
- * the dominant influence of salinity and sodicity, and
- * possible beneficial effects of other components.

(14) Some of the heavy metals introduced into the soil as a result of waste application are available for uptake by plants. The potential for significant food chain transfer is, however, low because only a small portion of the added metals are actually taken up by plants.

(15) In some cases, activities associated with drilling site construction and operation (e.g. topsoil disturbance, compaction) could result in greater damage to the soil than land application of the waste.

7.4 Mitigation

(16) The detrimental effects of land spreading of drilling wastes can be eliminated or reduced through such predisposal measures as:

- * selection of nontoxic drilling fluid additives,
- * reduction in volume of waste generated by means of recycling and reuse,
- * sump fluid treatment,
- * good housekeeping practices, and
- * consideration of alternate disposal methods (e.g. deep-well injection, approved disposal sites).

(17) Soil damage resulting from salinity can be reclaimed, through

leaching, by natural or artificial means in a relatively short time (several months to few years), depending on the severity of the problem, soil characteristics, site drainage and climatic conditions, particularly precipitation.

(18) Soil damage resulting from high sodium content of the waste can be mitigated through the use of appropriate amendments and leaching.

(19) Soil damage resulting from oil may be mitigated, at least in the topsoil, through tillage and proper fertilization.

7.5 Limitations

(20) The present study did not involve any field assessment.

(21) Of all the drilling mud studies reviewed, only two reports dealt with drilling waste effects under field conditions and none of those investigated the effects on agricultural soils and crops. Therefore, no quantitative assessment of the effects is possible. This would require comprehensive field investigations dealing with Saskatchewan crops, vegetation and soils and using the main types of drilling wastes used in the province. This is particularly important in view of the current deterioration in the quality of Saskatchewan soils (salinization, loss of organic matter and erosion) resulting from agricultural practices and climatic conditions.

8 RECOMMENDATIONS

(1) Firms engaged in drilling operations in the province should be encouraged to:

- * select the nontoxic or less toxic drilling fluid additives and drilling fluid systems,
- * reuse drilling fluids, particularly those identified to be detrimental to plants and soils,
- * plan site layout and pit design that will ensure proper containment of the waste, and
- * enforce appropriate housekeeping rules with emphasis on such aspects as minimizing volume of waste generated, chemical spills and site disturbances, and, where appropriate, separating the freshwater drilling wastes from the other types (e.g. salt base sump fluids).

(2) Agricultural land spreading, both on-site and off-site, of salt based drilling sump fluids and oil based sump fluids should be avoided. Firms using or planning the use of these fluid systems should employ other acceptable disposal options (e.g. subsurface disposal through deep-well injection, use of approved waste disposal facilities).

(3) Off-lease disposal of freshwater sump fluids could be continued with no significant impact anticipated, provided that the maximum application rates and quality criteria indicated in the Approval Guidelines developed by the Saskatchewan Energy and Mines are enforced.

However, it is recommended that areas with slopes exceeding 20% should be avoided and tillage prior to spreading be encouraged. Also, waste application on frozen soils should be avoided in order to minimize accumulation of excessive amounts of wastes in low-lying areas as a re-

sult of spring runoff.

An increase in the disposal rate to accommodate the anticipated intensive developments (e.g. directional drilling, enhanced oil recovery projects) may be possible, but the maximum safe level is not known and has to be established on the basis of field experimentation.

(4) On-lease disposal guidelines should be developed. Although appropriate field data necessary for the formulation of such guidelines are lacking at present, the following interim criteria, which are based on experience gained elsewhere (Section 5), are recommended:

- * maximum application rate of $290 \text{ m}^3/\text{ha}$ (730 bbls/acre)¹,
- * maximum chloride loading of 448 kg/ha (400 lbs/acre),
- * SAR <18,
- * total trace element loading:
 - boron = 4.5 kg/ha
 - chromium = 4.0 kg/ha
 - manganese = 10.0 kg/ha
 - molybdenum = 4.0 kg/ha
 - zinc = 50.0 kg/ha

(5) Disposal plans should take into consideration site suitability for disposal. Relative site sensitivity rating is given in Section 7.3 and soil sampling and analysis procedures are given in Appendix E.1

(6) Site reclamation guidelines should be developed. It is recommended that the objective of reclamation should be to restore the produc-

¹This is based on the 1:4 mud:soil ratio recommended by some U.S. reports, assuming an average topsoil depth of 10 cm (4"). This proposed maximum application rate is similar to that of Manitoba.

tivity to a level equal to or greater than the original conditions. The guidelines should consider the discussions included in Section 5.

(7) It is recommended that a list of recognized analytical laboratories, where the sump fluids and soils may be analyzed, be prepared. Active participation in the Canadian Quality Assurance Program should be the minimum qualification requirement.

(8) It is recommended that further studies be carried out to test the conclusions reached in this study under the Saskatchewan conditions, to provide quantitative data necessary for the formulation of environmental protection guidelines and to investigate the long-term effects of drilling waste disposal on agricultural land. These studies should include:

- * case studies to evaluate present on-site disposal practices and assess long-term effects of drilling waste disposal,

- * a comprehensive field assessment program involving application, at different rates, of the common sump fluids identified in the main oil producing regions,¹ and

- * development of a terrestrial toxicity test for use in sump evaluation since some effects could not be explained in terms of chemical analysis. Also, the types of wastes discharged into the sump are quite variable and are not always known.

¹ This could be supplemented by greenhouse studies. Field studies may be inconclusive due to weather, pests, soil variability, etc.

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